2017

PREDICITNG FAILURE OF CULVERTS AND ASSOCIATED IMPACTS IN LOW ORDER STREAMS OF NORTHERN MICHIGAN

Charles King
Michigan Technological University, chking@mtu.edu

PREDICITNG FAILURE OF CULVERTS AND ASSOCIATED IMPACTS IN LOW ORDER STREAMS OF NORTHERN MICHIGAN

By

C. Hunter King

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Forest Ecology and Management

MICHIGAN TECHNOLOGICAL UNIVERSITY

2017

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Forest Ecology and Management.

School of Forest Resources and Environmental Science

Thesis Co-Advisor:	*Joseph W. Wagenbrenner*
Thesis Co-Advisor:	*Andrew J. Storer*
Committee Member:	*Casey J. Huckins*
Committee Member:	*David W. Watkins*
Committee Member:	*Mark A. Fedora*
Committee Member:	*Melanie K. Watkins*
School Dean:	*Terry L. Sharik*

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Preface

This thesis, and the studies within were composed in collaboration with hydrologists, civil engineers, and ecologists at Michigan Technological University and the USDA Forest Service. Joe Wagenbrenner of the USDA Forest Service contributed to the design and analytics of this research project, along with the editing of this thesis. Joe Wagenbrenner, Casey Huckins, David Watkins, Mark Fedora, and collaborators from the University of Wisconsin and The Nature Conservancy conceived the project and obtained funding. The scope of this collaborative project was to refine estimates to add to FishWerks (greatlakesconnectivity.org), a Great Lakes Basin wide stream connectivity optimization tool.

Acknowledgements

The Great Lakes Fishery Trust, via a grant managed by the University of Wisconsin, and the USDA Forest Service provided funding for this research. Collaboration between the University of Wisconsin, Madison, USDA Forest Service and Michigan Technological University was essential to completing this thesis.

Thank you to my committee for their support, patience, and guidance through the duration of this project. Thank you to my advisor Dr. Joseph Wagenbrenner for all the revisions, instruction, intelligence, and expertise in the many fields within this research project. Thank you to Dr. Melanie Kueber-Watkins for her experienced guidance through the hydraulic modeling process in this study. Thank you to Dr. Casey Huckins and Dr. David Watkins for their assistance and recommendations in survey setup, data analytics, revisions and support during this research project. Thanks to our Forest Service collaborator, Mark Fedora, for his help in the study design, real-world experience, and direction in this project.

This research would not have taken place without help in the field, and in the lab compiling data. Many thanks to Sarah Harttung, Brian Danhoff, and Margaret Kloote for assisting with inventories and surveys.

Thank you to my friends and family, especially my parents, for their support throughout my entire educational career.

Abstract

The Great Lakes Region of North America has experienced more frequent extreme precipitation events recently, resulting in a large number of stream crossing failures. To evaluate failure risk and potential impacts of crossings in northern Michigan, we identified and conducted coarse assessments of all the stream crossings and dams in the North Branch Paint River Watershed. A subset of 11 culverts were selected from 49 identified sites for hydraulic analysis to estimate crossing failure discharge conditions. Stream crossing dimensions and upstream attributes were used to create metrics that predict failure risk without the need for complex hydraulic modeling, and these metrics were applied at the watershed scale. Sediment discharge and the economic impact associated with a failure event were also estimated for each stream crossing. Aquatic organism passability ratings were also determined for each crossing in the watershed. Five of the 11 modeled culverts were predicted to fail at discharges below the 50-year flood. Upstream main channel length, bankfull width, culvert width, and upstream watershed area formed the best metrics for predicting failure with a combined R^2 value of 0.9. Estimated cost of replacement was 19% more for a failed culvert than a planned replacement. Other unsurveyed culverts were analyzed to predicted failure condition discharge, and this resulted in an estimated cost of $1.4 million in total culvert replacement throughout the watershed for the 11 total culverts that would likely fail during a 50-year flood. Fish passability scores were lowest at culverts, and relationships between scores and risk of failure were assessed. Nine of the 20 culverts were impassable for fish year round, while 45% were barriers only at high flows. Risk of failure, in conjunction with organism passability, should be considered when prioritizing culverts for replacement.

1 Introduction

Most of the transportation infrastructure in service today is the result of the economic booms that took place in the USA in the 1950s and 1960s; thus many of the stream crossings are approaching the end of their design life, prompting the design of techniques to assess their risk of failure (Biswas et al., 2001; Mai et al., 2014). These infrastructures (dams, bridges, and culverts) can fragment fluvial systems, and act as potential barriers to morphologic and ecologic processes in rivers (Brandt, 2000; Nilsson et al., 2005). Potential barriers affect morphological processes such as nutrient and sediment transport (Williams and Wolman, 1984; Collier et al., 1998; Wood and Armitage, 1997; Liriano and Day, 2001; Stanley and Doyle, 2003; McNeely et al., 2007). Potential barriers also affect organism dispersal (Pépino et al., 2012). Fragmentation of river connectivity influences organism population dynamics in terms of migration for reproduction, forage, refuge, and other life history traits (Warren and Pardew, 1998; Roni et al., 2002; Bowler and Benton, 2005; Nagrodski et al., 2012). Incorporating risk of failure techniques, along with stream connectivity impacts, in prioritization schemes to assess needed action at a potential barrier will optimize budgets, while restoring aquatic organism passage (AOP).

Prioritization of stream habitat restoration is a general term used for the step-by-step process of methods used by water resources managers, ecologists, and engineers to make decisions about the addition, alteration, or removal of potential barriers and other changes to improve the structure of riverine systems (McKay et al., 2016). The purpose of barrier removal or replacement projects is mainly to increase stream connectivity, or passability, for aquatic organisms. Prioritization provides a mechanism to optimize restoration under some constraint, usually financing. Common prioritization techniques include scoring, ranking, optimization or scenario analysis (Schick and Lindley, 2007; Hicks and Sullivan, 2008; Mount et al., 2011; King and O'Hanley, 2014; McKay et al., 2016). Progress in planning and prioritization process development has increased as barrier information becomes more widely available at larger spatial scales, allowing tools such as FishWerks (Moody et al., 2017, greatlakesconnectivity.org) to maximize the efficiency of connectivity improvement projects at the Great Lakes Basin scale.

As of 2013, Januchowski-Hartely et al. (2013) identified 276,027 potential aquatic organism barriers in the Great Lakes Basin, 97% of which were stream crossings. Within this population of stream crossings were bridges, which generally do not hinder aquatic organism passage and have relatively low likelihood of failure. The predominant type of stream crossings were culverts, which can significantly influence passability. Culverts cost less to install than bridges, resulting in their more widespread use (Gibson, 2005). Approximately 34% of stream crossings in the Great Lakes Watershed are impassable while 29% are partially passable, implying that around 170,000 crossings may impact connectivity for fish (Januchowski-Hartely et al., 2013).

An extensive amount of literature has proposed methods to prioritize barrier repair or removal to improve the opportunity for fish passage. McKay et al. (2016) reviewed 46 studies that examined barrier prioritization, and identify three steps in the prioritization process: establish the geographic extent of analysis, select a focal taxon, and identify management actions. The basis of these analyses is organism passage, and minimal consideration is given to prioritize a culvert based on its ability to convey potential flood flows and associated sediment or debris.

In the last two decades, the northern Great Lakes Basin has experienced several major flood events. In Marquette County, Michigan on May 13, 2003, substantial rains caused two dams to fail, one of which released over eight billion gallons of water creating damage to three other dams, and damage or destruction of nine bridges (Nault and Hayes, 2003). On June 20, 2012, 10.1 inches of rain fell in Duluth, Minnesota, greatly exceeding the area’s 100-year 24-

hour storm depth of 6.9 inches (Graning and Hluchan, 2012). Damage to public infrastructure was estimated to cost upwards of $80 million (Cadotte, 2012), and the Federal Emergency Management Agency (FEMA) approved over $43.5 million in public assistance for the disaster (FEMA, 2012). Another major flood occurred in October 2012 in the Canadian city of Wawa, Ontario. Every road in and out of town became impassable, stranding the 3,000 residents. Highway 101, the only road leading to a community of 700, was washed out at a stream crossing preventing access to food, medicine and other human necessities (Kelly, 2012). Unpublished data from a flood that occurred in Northern Wisconsin on July 11, 2016 estimated flows at culvert failure sites that were 7.5 times greater than the 500-yr flow estimates (Dale Higgins, USDA Forest Service, 2017 unpublished data). Estimated damage to public infrastructure cost $26 million (Kaeding, 2017).

Culvert failure conditions are complex and variable in nature. The two main failure conditions are inadequate flow capacity and structural collapse (Lian and Yen, 2003). The Great Lakes Basin is at risk of substantial increase in ‘great’ flood events according to climate change simulations composed by Milly et al. (2002). Thus, failure at culverts may become more common due to inadequate and outdated design. Structural collapse may also occur when the structure cannot handle a freight load (i.e. crushed), or prolonged erosional process at the culvert (Lian and Yen, 2003).

Research has been integrated in culvert design to account for varied estimated flood discharges (Hager et al., 1998; FHWA 2012; Cafferata et al., 2004). Less effort has been put forth towards inventorying and prioritizing stream crossings that have a higher potential of failing under estimated flood values. Fitzgerald and Clifton (1998) inventoried 86 stream crossings in a watershed of southeast Washington and northeast Oregon after flooding in winter 1995-1996. Their analysis found that 51% of the crossings failed, and that sediment and wood restricted flow at the majority of these failed crossings. Examination of failed culverts in the Pacific Northwest by Cafferata et al. (2004) concluded that large woody debris and sediment caused reduction in flow capacity, and this was the most common mechanism of culvert failure. They recommend the headwater depth to culvert diameter ratio (HW/D) be no larger than 1 in lower sloped watersheds, while no larger than 0.67 in mountainous watersheds with high slopes to accommodate wood and sediment passage associated with flood flows. Piehl et al. (1988) also argue that failure at a culvert has potential to occur when HW/D>1.

Given the increase of large storm events in the Great Lakes Basin, assessing the risk of culvert failure should be included in regional prioritization techniques. However, tools to predict flows and hydraulic conditions at culverts are complex and data intensive, and there is a need to develop simple assessment procedures from readily available data. This study assessed the vulnerability of culverts in the North Branch Paint River, Iron County, Michigan, USA (Figure 2.1), to failure at high flows by determining the maximum capacity that the culverts can withstand before failure. Peak discharge estimates over a range of return periods were established under current climatic conditions. Predictors of culvert failure were assessed through testing ratios created from GIS-derived measurements and coarse level survey data. Multiple linear regression was used to predict the failure condition at every non-surveyed culvert in the watershed. We also assessed the habitat connectivity impacts of potential barriers for resident fish passability using established criteria. Finally, cost estimates for planned culvert replacements and replacements after failure were estimated and compared.

2 Methods

Stream crossings in the North Branch Paint River watershed were identified, surveyed, and analyzed. A subset of crossings was used for in-depth analysis, and the results from this sample were extended to the watershed scale.

2.1 Research Area and Description

The research area consisted of the North Branch Paint River (North Branch) watershed located in the Ottawa National Forest of Michigan's Upper Peninsula (Figure 2.1). As of 2011, landuse in the 116.9 mi^2 North Branch was 66.9% forested, 30.7% open water or wetland, and 2.4% developed (Homer, 2015). Of the forests, 41.4% were coniferous, 40.9% were deciduous, and 17.6% were a mixture of both (Homer, 2015). Glacial deposits dominated by sand (68%) and silt (28%) were composed of soil classes of spodosols (68.9%), inceptisols (27.7%), and histolsols (16.7%) in the watershed (Soil Survey Staff, 2017). The North Branch had an average saturated permeability rate of 7.3 $inhr^{-1}$ and a mean slope of 2.7% (Soil Survey Staff, 2017; NRCS, 2017). Average monthly precipitation in Amasa, MI, 14 miles east of the North Branch watershed boundary, was 2.3 inches per month from 1997-2017 (NCEI, 2017). Spring snowmelt is a dominant hydrologic influence in the Upper Peninsula, and an average of 212 in yr^{-1} of snow fell in Kenton, MI, 7 miles north of the North Branch watershed Boundary, from 2005-2016 (Damon Haan, USDA Forest Service, 2017, unpublished data). The North Branch stream orders range from 1 to 4 (Strahler, 1957), and the Paint River is a tributary to the Menominee River and Lake Michigan.

An assessment using satellite and near surface remote imagery analysis determined the North Branch to have a road density of 5.2 miles of road per square mile, with a total of 605 miles of road in the watershed (Banach et al., 2016). These data identified 58 potential fish passage barriers in the North Branch, including dams, culverts, bridges, fords, footbridges, and removed crossings (Banach et al., 2016). This number was greater than the number of crossings detected by the intersection of the total flow line with the State of Michigan's "All Roads" shapefile, which suggested 27 stream crossings (State of Michigan, 2014). The Banach et al. (2016) data also had more crossings than data previously used by the Forest Service, which indicated that roads intersected the North Branch at 36 points (Amy Amman, USDA Forest Service, personal communication, 14 Nov 2017). The differences among the data sets are due to the inclusion of all roads and trails in the remotely sensed data set assembled by Banach et al. (2016), including decommissioned routes, as well as dams. Extensive ground reconnaissance via hiking and paddling in summer 2016 identified 49 potential barriers.

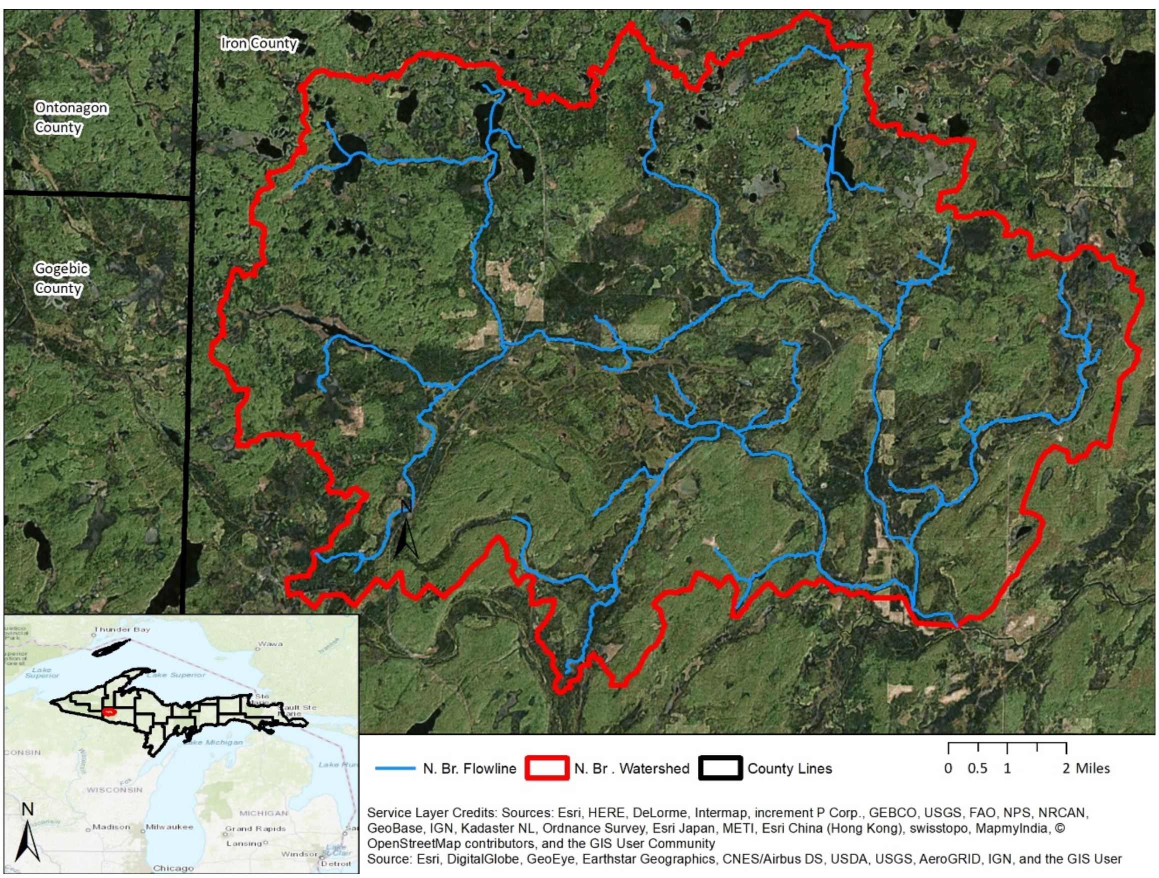

Figure 2.1: Location of the North Branch Paint River Watershed in Iron County and the Upper Peninsula of Michigan.

2.2 **Coarse Resolution Inventories**

The 49 crossings and dams were inventoried in May and June 2016 following the Great Lakes Road Crossing Inventory Instructions (GLRCII) (GLRSCII, 2011) (Appendix A). Qualitative observations included crossing type, construction material, and condition of the crossing. Measurements included road width, structure height, structure length, structure width, stream bankfull width, wetted width, and average wetted depth. Road characteristics such as approach length, slope, and adjacent low point were measured, and road fill depth above the culvert was estimated. Thalweg stream velocities were measured at the inlet and outlet of each structure, and in the stream where the channel was not apparently impacted by the crossing, with a handheld acoustic doppler velocimeter (SonTek, San Diego, CA, USA).

Fish passability ratings at each potential barrier (Diebel et al., 2009), were determined based on water depths and velocities and outlet perch height. Scores were assigned as follows: 0 indicated that most fish at all life stages would not be able to pass the structure; 0.5 indicated some species at different life stages would be able to pass; 0.9 suggested the structure was a barrier only at high flows; and 1 indicated the structure was not a barrier (Diebel et al., 2009). Velocities and passability ratings were for observed flow conditions, which varied from approximately half bankfull to bankfull.

2.3 **High Resolution Surveys**

Eleven culverts were chosen for high-resolution surveys and hydraulic modeling to predict flow conditions at failure. Five of the nine culverts with passability ratings of 0 were randomly selected (Figure 2.2). Six surveyed culverts were randomly selected from the remaining 11 culverts with passability scores greater than 0 (Figure 2.2). At each culvert, the coordinates of the road prism, culvert inlet, culvert outlet, and flood plain and stream channel along four cross-sections were surveyed with a total station. A total station is an electronic distance measurement instrument that determines the spatial coordinates of the position identified using a reflecting prism by reflectance and angle measurements. From multiple point measurements, elevation surfaces, and distances and slopes between points can be derived.

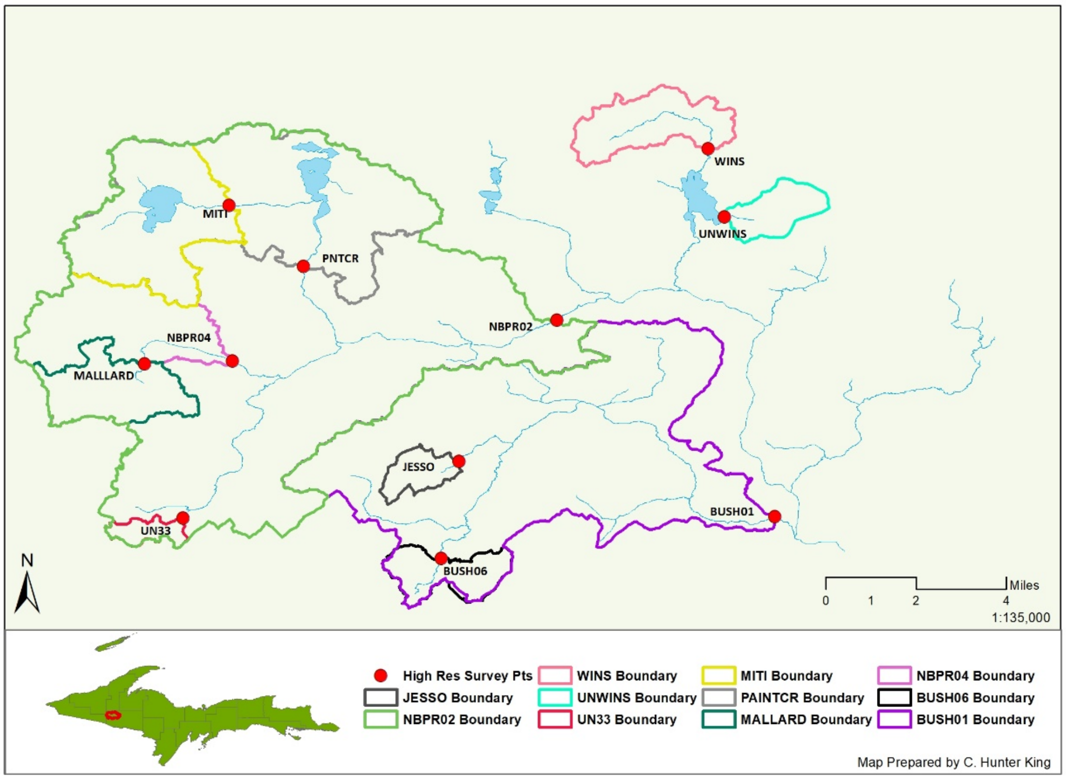

Figure 2.2: Location, site identifier, and subwatershed of each high resolution survey site in the North Branch.

We surveyed two cross sections upstream, and two cross sections downstream of each culvert, and extended each cross section into the floodplain. The cross sections located farthest from the culvert were selected so that channel and floodplain were not apparently impacted by the culvert. The other two cross sections were located within 10 m of the inlet or outlet to represent flow contraction and expansion conditions at the culvert. Thalweg channel elevations were surveyed beyond the farthest upstream and downstream transects to establish channel slopes near the culvert.

Elevation points on the road prism, the trapezoidal cross-sectional shape composed of the road tread and fill which crosses the floodplain, were also surveyed. Road prism points were measured at the top of the road, approximately half way down each fill slope, and at the point where the road fills met the floodplain (Figure 2.3). These measurements were made at approximately equidistant intervals along the road averaging between 15 and 40 ft spanning the floodplain width (e.g. Figure 2.3). Total station surveys averaged 203 points per site and ranged from 146 to 267 points per site. High resolution surveys were done in August 2016 and May 2017.

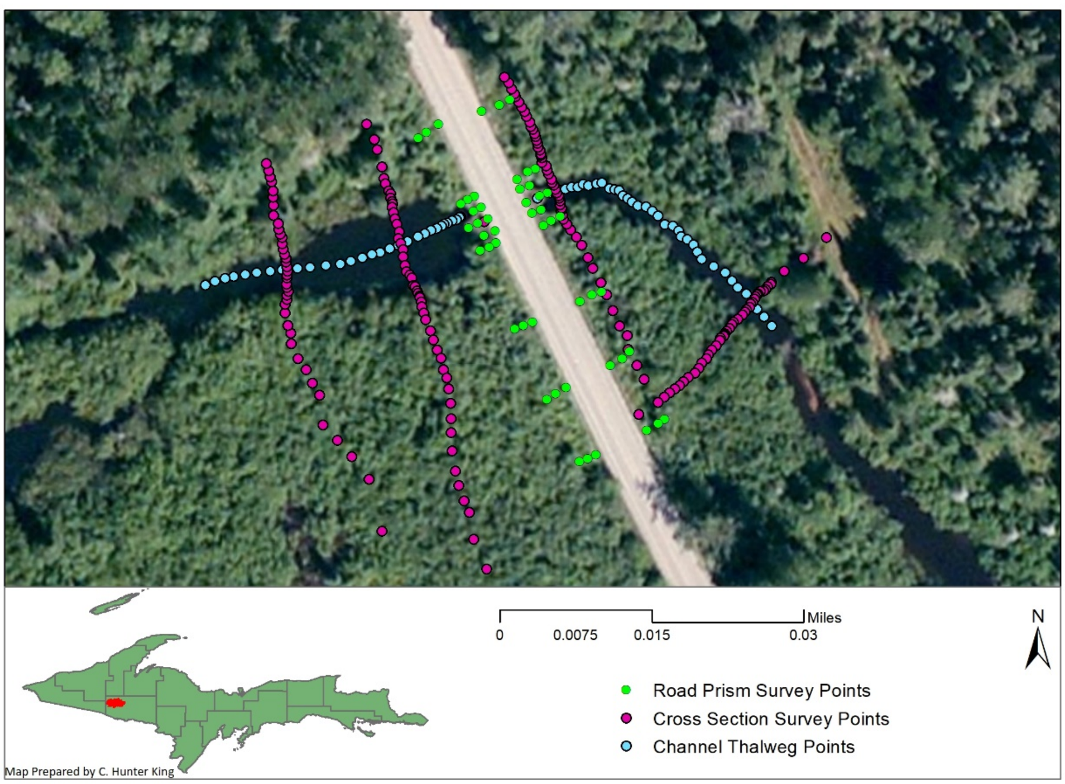

Figure 2.3: Cross section, road prism, and thalweg survey points at BUSH01.

2.4 **Estimating Flood Discharge Values for Culverts in the North Branch**

There is no streamflow gage in the North Branch watershed, thus gaged reference reaches were used to select a method for estimating stream flows. Gages on the Black River, Middle Branch Ontonagon River, and the Iron River are located 13-68 miles from the outlet of the North Branch (Table 2.1). Log Pearson Type III (LP3) probability analysis of annual peak discharge values was used to determine return periods of the observed flows at the gaged sites (USGS, 1982).

Table 2.1: River Name, USGS gage number, distance from the North Branch, upstream watershed area, and length of record for each reference gage used to establish flood discharge values for the ungaged North Branch (USGS A; B; C, 2016).

River Name	USGS Gage Number	Distance from N. Br. Outlet (mi)	Watershed Area (mi^2)	Length of Record (years)
Black River	4031000	68	200	45
Iron River	4060500	13	92	45
Mid. Br. Ontonagon River	4033000	19	164	70

Values from four peak discharge models were calculated from watershed attributes (Table 2.2) for each reference stream. The four models were: USGS Wisconsin Zone 4 regression equation (Walker and Krug, 2003); USGS Michigan Zone 1 regression equation (Holtschlag and Crosky, 1984) using the 1961 (USDC, 1961) and 2013 (NOAA, 2013) estimates of 100-yr, 24-hr precipitation; and the Michigan Department of Environmental Quality's (MDEQ) method for computing flood discharges for small ungaged watersheds (Sorrell, 2010) (Table 2.2).

Input values for the four models were derived from GIS (ESRI, 2017). Contributing area was derived from a 10-meter digital elevation model (DEM) (NRCS, 2017) using hydrology tools in ArcGIS (ESRI, 2017). Main channel slope was computed as the difference in elevation between points at 10% and 85% of the watershed's hydraulic length above the culvert, where 100% is the watershed boundary, divided by the stream distance between points. The hydraulic length is the linear distance of the longest flow path in a watershed. River channel length adjacent to wetland and open water was determined as the length of intersect of the watershed's main flow line and the National Wetlands Inventory's designated wetlands layer (Cowardin et al., 1979). Slenderness ratio was determined by squaring the hydraulic length (mi) and dividing by the contributing area (mi^2). Soil characteristics were clipped to the watershed boundary from the State of Michigan's Quaternary Geology layer, and the percent of each soil type within the watershed was identified (Farrand and Bell, 1982).

Table 2.2: Flood discharge methods, models inputs, and sources of models used for comparison to gaged values in reference streams.

Method	Geomorphic and Climate Inputs	Source
Wisconsin Zone 4 Regression Equation	Contributing watershed area (mi^2) Water storage in watershed (%) Main channel slope (ft mi^{-1}) Soil permeability in watershed (in hr^{-1}) Average annual snowfall (in)	Walker and Krug, 2003
Michigan Zone 1 Regression Equation	Contributing watershed area (mi^2) Hydraulic length (ft) Main channel slope (ft mi^{-1}) Length of stream adjacent to lake or wetland (ft) USDC, 1961 or NOAA, 2013 100 yr-24 hr precipitation intensity (in hr^{-1}) Quaternary soil type 2, 3, 5, 7, 8, 10-13, 15 (%)	Holtschlag and Crosky, 1984
MDEQ	Contributing drainage area (mi^2) MI Zone 1 100 yr-24 hr precipitation intensity (5.32 in hr^{-1}) Time of concentration (hours) Rainfall runoff curve number	Sorrell, 2010

Estimated discharge values from each of the reference gage sites were compared with discharge estimates for the North Branch using linear regression. The USGS Michigan Zone 1 regression equation using the 2013 precipitation intensity best fit the LP3 peak discharge estimates across the three reference gages (Appendix B). This equation was used to predict the discharge at each culvert as an input to the hydraulic model (Section 2.5). Michigan Zone 1 regression equations and the associated inputs are shown in Appendix C.

2.5 **Hydraulic Modeling of Culverts**

We simulated a river reach from the cross section and longitudinal survey data in the Hydrologic Engineering Center-River Analysis System 5.0.3 (HEC-RAS) modeling software (U.S. Army Corps of Engineers, 2016). Manning's n values for the right and left floodplain, the channel, and the culvert were derived from a reference table (Brunner, 2016). Subcritical flow contraction and expansion coefficients, weir coefficients, entrance and exit loss coefficients and other culvert data were obtained from the HEC-RAS guidelines (Brunner, 2016) for each modeled site.

Culvert information, including construction material, length, height, width, and headwall conditions, was obtained from the coarse surveys. Discharge (Q) values derived from the regression equations (Section 2.4) were used to predict flow depths at the culvert for the 2, 5, 10, 25, 50, 100, 200, and 500-year return period flows. We assumed that failure would occur at a headwater depth to culvert diameter (HW/D) ratio of 1 and calculated the discharge at failure (Qtop) for each modeled culvert through iterative model runs. The return period for the failure discharge was derived from the best-fit equation between discharge and return interval for each modeled culvert.

2.6 **Predicting Failure at a Culvert**

A failure ratio was used to normalize failure flows across surveyed culverts. The ratio was the estimated Qtop divided by the 50-year discharge value (Q50) derived from the USGS regression equation (Section 2.4). Q50 was selected as it is a common discharge used for designing culverts (FWHA, 2012). Failure ratios greater than 1 indicated failure would occur at a discharge greater than Q50. Similarly, ratios less than 1 indicated failure would occur at a discharge less than Q50. Because the precise flood recurrence interval associated with culvert failure was indistinguishable at discharges greater than 500-year interval, use of this ratio also reduced the impact of individual Qtop values that exceeded 500-year return intervals.

Watershed attributes (Appendix E), culvert dimensions (Appendix F), and upstream bankfull conditions (Appendix G) were correlated with failure condition across sites. These measurements and attributes were used to create metrics that might predict the failure condition at other culverts without the step of hydraulic modeling. In total, 61 metrics (Appendix H) were calculated and tested. Linear regression was used to examine relationships between each metric and the failure ratio using the correlate function in R (R Core Team, 2013) in RStudio (RStudio Team, 2015). R^2 values greater than 0.3 indicated significant correlation between the metrics and failure condition across surveyed sites.

Multiple linear regression was also used to assess the failure condition. A model was built through forward selection to predict failure at other culverts in the North Branch that were not surveyed at high resolution. The independent culvert measurement with highest correlation to failure condition was used (Appendix F). Similarly, the bankfull condition and watershed attribute with the highest R^2 value was used in the multiple linear analysis (Appendix G, Appendix E). Watershed area was also used in the linear analysis.

2.7 Economic Implications of Culvert Failure

We assessed the cost of a culvert failure by comparing the cost of a planned culvert replacement (T_P), to the cost of a replacement after culvert failure (T_F) at the same site. Adaptions to Perrin and Jhaveri's (2004) life cycle cost analysis for replacing culverts were used to estimate T_P:

$$T_P = C_R + C_{SP} + C_{DP} \text{..........Equation 1}$$

where C_R is the cost of replacement, C_{SP} is the cost of service associated with a planned culvert replacement, and C_{DP} is the cost of user delay associated with planned culvert replacement. The cost of culvert failure (T_F) was estimated by

$$T_F = C_R + C_{SF} + C_{DF} + C_{GF} + C_{EF} \text{……….Equation 2}$$

where C_R is the cost of replacement, C_{SF} is the cost of service associated with a failed culvert replacement, C_{DF} is the cost of user delay associated with failed culvert replacement, C_{GF} is the cost to replace lost road fill, and C_{EF} is the cost to remove sediment mobilized into the channel after failure.

Data from Great Lakes Road Crossing Inventory surveys in northern Wisconsin were used to create a Microsoft Access (Microsoft Corp., 2017) tool to estimate C_R (Diebel, 2009). Inputs from the coarse survey are: structure type, bankfull width, structure length, structure width, road width, road surface type, and fill depth above culvert. This tool was used to establish estimates of C_R in 2009 dollars, and we applied an annual inflation rate of 1.7% to convert to 2017 dollars (BLS, 2017). Fixed costs in this tool are shown in Table 2.3:

Table 2.3: Fixed cost type and amount in 2009 $ used in estimating C_R

Type	Excavation ($\$/yd^3$)	Backfill ($\$/yd^3$)	Bedding ($\$/yd^3$)	Crown Fill ($\$/yd^3$)
Cost (2009 $)	12	8	16	6

Service cost (C_S) is an estimate for the cost of oversight and engineering associated with replacing a culvert. We used a C_S value of 20% of C_R to estimate total planned cost (T_P) (O'Shaughnessy et. al., 2016). Data for personnel costs during emergency replacement are not readily available, so we assumed 30% of C_R to cover overtime cost and estimate the total failure cost (T_F).

The cost of loss of use, or user delay (C_D) after a culvert failure, was estimated using the approach of Perrin and Jhaveri (2004):

$$C_D = T \times H \times D \times (C_P \times V_P \times V_O + C_F \times V_F)\text{……….Equation 3}$$

where T is the annual average daily traffic, which is estimated at 10 cars for forest roads in the Ottawa National Forest. H is the amount of delay in hours, and we assumed one hour of delay time based on the approximate speed and distance needed to detour around any single failed crossing (Banach et al., 2016); and D is the number of days the road is unpassable. We assumed a D of 2 days for planned replacements based on personal experience with culvert replacements, and 10 days for a failed replacement (Mark Fedora, USDA Forest Service, personal communication, 31 Oct 2017). C_P is the cost per person hour, which was estimated at $24 per hour by inflating 2002 dollars at 2.1% to 2017 dollars (USDL, 2002; BLS, 2017). V_P is the percent of passenger vehicle volume, which was estimated at 97% (TRB, 2000); and V_O is the vehicle occupancy, which was estimated at 1.2 people per vehicle (Perrin and Jhaveri, 2004). C_F is the cost per freight hour, estimated at $70 per freight hour by inflating 2002 dollars at 2.1% to 2017 dollars (USDL, 2002; BLS, 2017), and V_F is the percent of freight traffic volume, which was estimated at 3% (TRB, 2000).

Failed culverts would contribute sediment from the road prism to the stream channel, and this material would need to be replaced to re-open the crossing and would also need to be removed from the stream to return it to its pre-failure condition. The cost of fill replacement (C_G) was determined from estimating the total volume of fill that was mobilized from the road prism during failure. The lost volume was conservatively estimated by multiplying the road prism cross-sectional area times the downstream bankfull width, and subtracting the culvert volume (Figure 2.4).

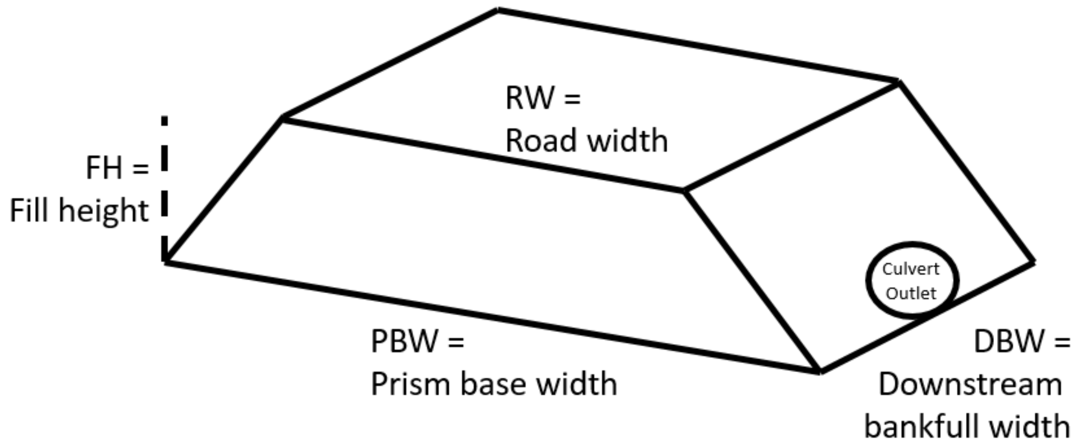

Figure 2.4: Road prism dimensions

This gives:

$$Lost\ volume = \frac{RW+PBW}{2} \times FH \times DBW - culvert\ volume \text{..........Equation 4}$$

Culvert volume will vary with the shape of culvert, typically cylindrical or rectangular. Cost of sediment replacement (C_G) assumes an average of \$29/yd^3 of lost sediment (Neeson et al., in review).

The estimated cost for sediment removal from the stream (C_E) is \$25/yd^3 of lost sediment plus \$4160 per day in operator and additional costs (Brian Halm, Streamside Environmental, personal communication, 27 Oct 2017). The dredge is able to remove 750 yd^3/day, and therefore would only be needed for one day for each site in the North Branch. Sediment removed from the stream would be deposited at a site located near the failed crossing, outside of the floodplain. The cost of removal of the sediment from the stream is one method to determine the economic value of the degradation of the ecosystem attributed to the culvert failure (Loomis et al., 2000).

3 Results

3.1 Coarse Resolution Inventory

Ground surveys led to the confirmation of 49 potential barriers, which include 20 culverts, 19 bridges, 8 dams, and 2 fords, and exclude removed crossings (Figure 3.1). This is nine less that the MTRI analysis for barriers in the watershed (Banach et al., 2016). Seventy-five percent of inventoried culverts occurred on first-order streams in the North Branch. Details of each potential barrier, including the type, material, dimensions and fish passability score, can be found in Appendix D.

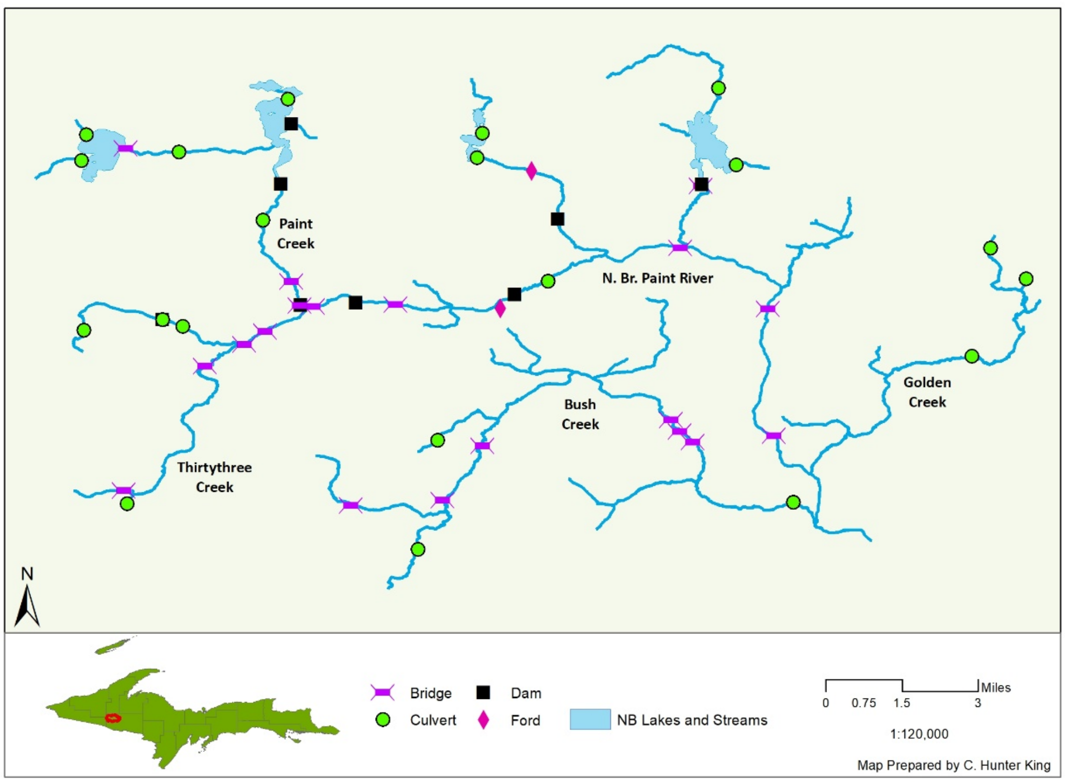

Figure 3.1: Inventoried potential barrier type and location in the North Branch (does not include removed crossings).

Fish passability scores were given to each potential barrier. Thirty-five percent of all potential barriers had a passability score of 1, and 37% had a score of 0 (unpassable) (Figure

3.2). The majority of the remaining 28% of the barriers had a score of 0.9, indicating they would be barriers to passage only at high flow periods. Every dam in the watershed was unpassable. Every ford, 74% of the bridges, and 5% of the culverts had passability score of 1, allowing fish at all life stages to mobilize upstream and downstream (Figure 3.2). Forty-seven percent of the culverts were unpassable all year for fish at every life stage. The single bridge with the passability score of 0 was a decrepit all-terrain vehicle bridge constructed of logs and planks without any structural support spanning the river, causing debris build-up and scour. Eight of the ten crossings (excluding dams) with passability ranking of 0 occurred on first-order streams.

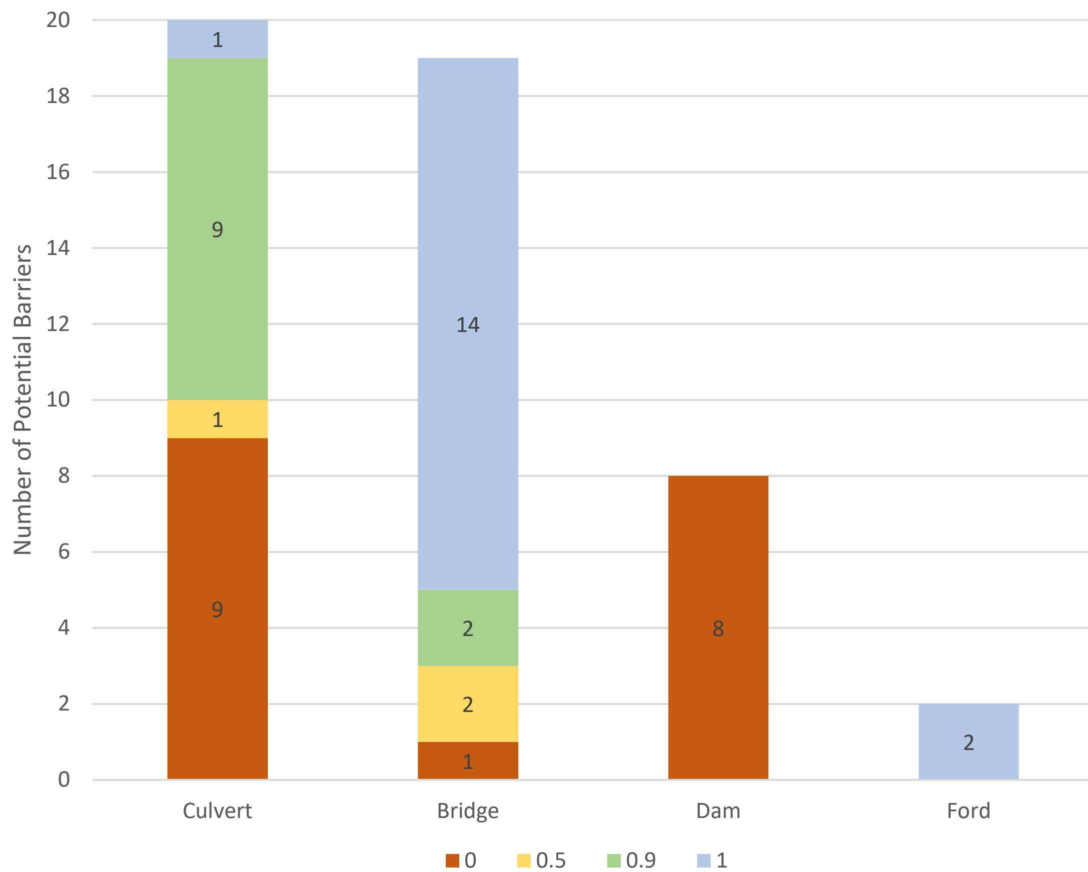

Figure 3.2: Number of potential barriers in each fish passability rating category by stream crossing type.

3.2 **Flood Discharge at Culverts in the North Branch**

Subwatershed drainage area (DA) upstream of analyzed culverts ranged from 0.5 mi^2 at JESSO to 46.6 mi^2 at NBPR02 (Table 3.1). The average main channel slope upstream of culverts was 0.38%, with maximum slope above JESSO (0.97%) and minimum slope occurring above NBPR04 (0.08%) (Table 3.1). Each location was assumed to have a 100-yr, 24-hr precipitation value of 5.81 in hr^{-1} (NOAA, 2013). Table 3.1 shows other inputs used in the USGS regression equation. Estimated discharge (Q) values for the 2, 5, 10, 25, 50, 100, 200, 500-year flood event at each of the 11 culverts surveyed are shown in Table 3.2. Q2 ranged from 6 to 21 $ft^3\ s^{-1}\ mi^{-2}$, and Q500 ranged from 24 to 129 $ft^3\ s^{-1}\ mi^{-2}$ across sites. Average Q50 at culverts in the North Branch was 43 $ft^3\ s^{-1}\ mi^{-2}$.

Table 3.1: Attributes for each surveyed location used in the USGS Michigan Zone 1 regression equation.

Site	Drainage Area	Main Channel Slope	Main Channel Adjacent to Swamp	Slenderness Ratio	100 yr, 24 hr Precipitation intensity	Glacial Outwash	Bedrock	Glacial Coarse Till
units	mi^2	%	%		$in\ hr^{-1}$	%	%	%
BUSH01	24.1	0.24	87.2	8.0	5.8	14.1	9.3	76.6
BUSH06	1.6	0.69	73.9	1.5	5.8	0.0	0.0	100.0
JESSO	0.9	0.97	69.2	3.1	5.8	0.0	0.0	100.0
MALLARD	2.8	0.39	76.7	1.2	5.8	0.0	0.0	0.0
MITI	6.1	0.50	75.7	2.3	5.8	0.0	0.0	0.0
NBPR02	46.1	0.12	75.4	3.6	5.8	15.2	2.2	11.1
NBPR04	7.3	0.08	89.0	2.0	5.8	0.0	0.0	0.0
PAINTCR	14.1	0.20	86.5	3.7	5.8	2.4	0.0	0.0
UN33	0.5	0.35	69.9	3.9	5.8	0.0	0.0	100.0
UNWINS	0.5	0.39	65.2	2.9	5.8	0.0	0.0	0.0
WINS	2.6	0.25	90.2	4.8	5.8	0.0	0.0	0.0

Table 3.2: Estimated discharge at given return intervals across the surveyed sites in the North Branch.

Site	Q2 (ft^3 s^{-1})	Q5 (ft^3 s^{-1})	Q10 (ft^3 s^{-1})	Q25 (ft^3 s^{-1})	Q50 (ft^3 s^{-1})	Q100 (ft^3 s^{-1})	Q200 (ft^3 s^{-1})	Q500 (ft^3 s^{-1})
BUSH01	205	308	375	471	551	635	710	823
BUSH06	32	55	71	95	116	140	162	196
JESSO	18	31	40	54	66	79	92	111
MALLARD	42	67	85	112	134	159	181	215
MITI	82	132	165	215	257	304	345	409
NBPR02	286	426	516	645	750	863	962	1,111
NBPR04	67	104	128	164	192	224	252	295
PAINTCR	112	172	212	269	316	368	413	482
UN33	10	16	20	27	32	38	44	53
UNWINS	9	14	17	23	27	32	36	43
WINS	30	47	58	74	88	103	116	137

Eight of the 11 modeled culverts exceeded a headwater depth to culvert diameter (HW/D) ratio of 1 at discharges with return periods less than 500 years (Table 3.3). Failure discharge (Qtop) ranged from 2 $ft^3\ s^{-1}\ mi^{-2}$ at PAINTCR to 280 $ft^3\ s^{-1}\ mi^{-2}$ at BUSH06. Three return intervals exceeded 500 years, and we classified these as >500-yr events. The minimum return interval for the failure flows was 1 year. Five of the culverts were predicted to fail at return intervals less than 50 years (Table 3.3).

Table 3.3: Predicted failure discharge (Qtop), specific discharge at failure (qtop), design discharge (Q50), specific design discharge (q50), return interval of failure discharges, and failure condition ratio for each surveyed site in the North Branch.

Site	Discharge at Failure (Qtop)	Specific Discharge at Failure (qtop)	Design Discharge (Q50)	Specific Design Discharge (q50)	Failure Return Interval	Qtop/ Q50= Failure Ratio
	$ft^3\ s^{-1}$	$ft^3\ s^{-1}\ mi^{-2}$	$ft^3\ s^{-1}$	$ft^3\ s^{-1}\ mi^{-2}$	years	
PAINTCR	24	2	316	22	1	0.08
JESSO	20	23	66	77	3	0.3
UN33	29	54	32	61	27	0.89
UNWINS	24	49	27	52	34	0.9
MITI	233	38	257	42	30	0.91
WINS	97	37	88	34	73	1.10
MALLARD	155	55	134	49	88	1.16
NBPR02	1,349	29	750	16	210	1.8
NBPR04	429	59	192	26	>500	2.23
BUSH01	1,713	71	551	23	>500	3.11
BUSH06	449	280	116	73	>500	3.86

3.3 **Predictors of Culvert Failure**

From linear regression analysis comparing the 61 metrics with culvert failure ratio, seven metrics that compared a culvert measurement with an upstream attribute were identified to have an R^2 greater than 0.3 (Table 3.4). Of these metrics, two are shown in Figure 3.3 and 3.4. The first metric is culvert width times main channel length divided by watershed area ((ft x ft) / ft^2) ($R^2 = 0.70$) (Metric a, Table 3.4), where main channel length is the distance of the major contributing tributary upstream of the crossing. Total channel length (i.e. Metric c) is the combined length of every contributing tributary upstream of the crossing. This metric implies that failure condition is more likely when a narrower culvert is placed at a location with a relatively wide mean upstream watershed width (Figure 3.3).

The second metric that correlated strongly with failure ratio is culvert width divided by bankfull width (ft / ft) ($R^2 = 0.37$) (Metric g, Table 3.4), which represents the degree of channel constriction. This metric implies that when the channel is constricted by a culvert, the probability of failure increases. Five other metrics that compare a culvert measurement with upstream attribute with an R^2 value greater than 0.3 were also noted (Table 3.4).

Table 3.4: Metrics, units, correlation coefficient, coefficients of determination, and p-value for the metrics that showed strong correlation to culvert failure (R^2>0.3)

Metric	Metric description	Units in equation	R	R^2	P
a	culvert width x main channel length / watershed area	(ft x ft) / ft^2	0.84	0.70	0.07
b	culvert width x hydraulic length / watershed area	(ft x ft) / ft^2	0.80	0.64	0.09
e	culvert length x total channel length / watershed area	(ft x ft) / ft^2	0.68	0.47	0.15
f	culvert width / hydraulic length	ft / ft	0.67	0.45	0.21
g	culvert width / bankfull width	ft / ft	0.61	0.37	0.08
h	culvert length x total channel length / watershed area	(ft x ft) / ft^2	0.61	0.37	0.06
i	culvert inlet area / watershed storage area	ft^2 / ft^2	0.60	0.36	0.29

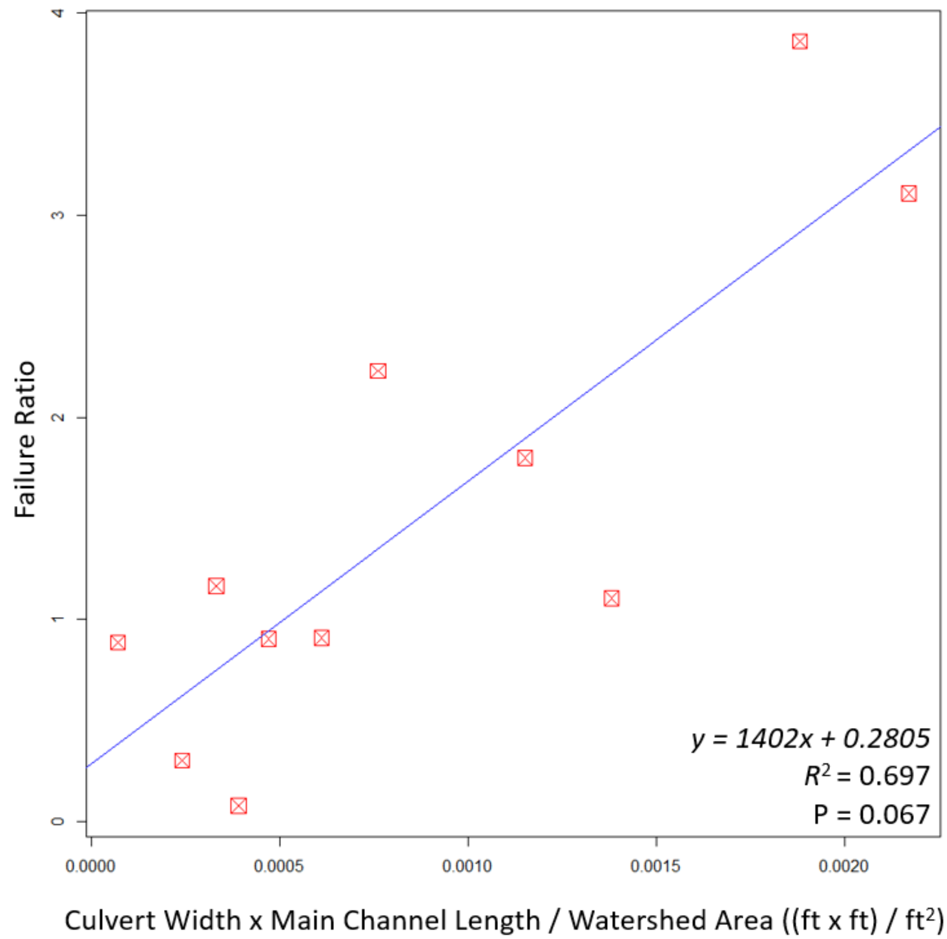

Figure 3.3: Linear regression between failure ratio and metric a (culvert width x main channel length / watershed area (ft x ft / ft^2)), for the sample of 11 surveyed sites.

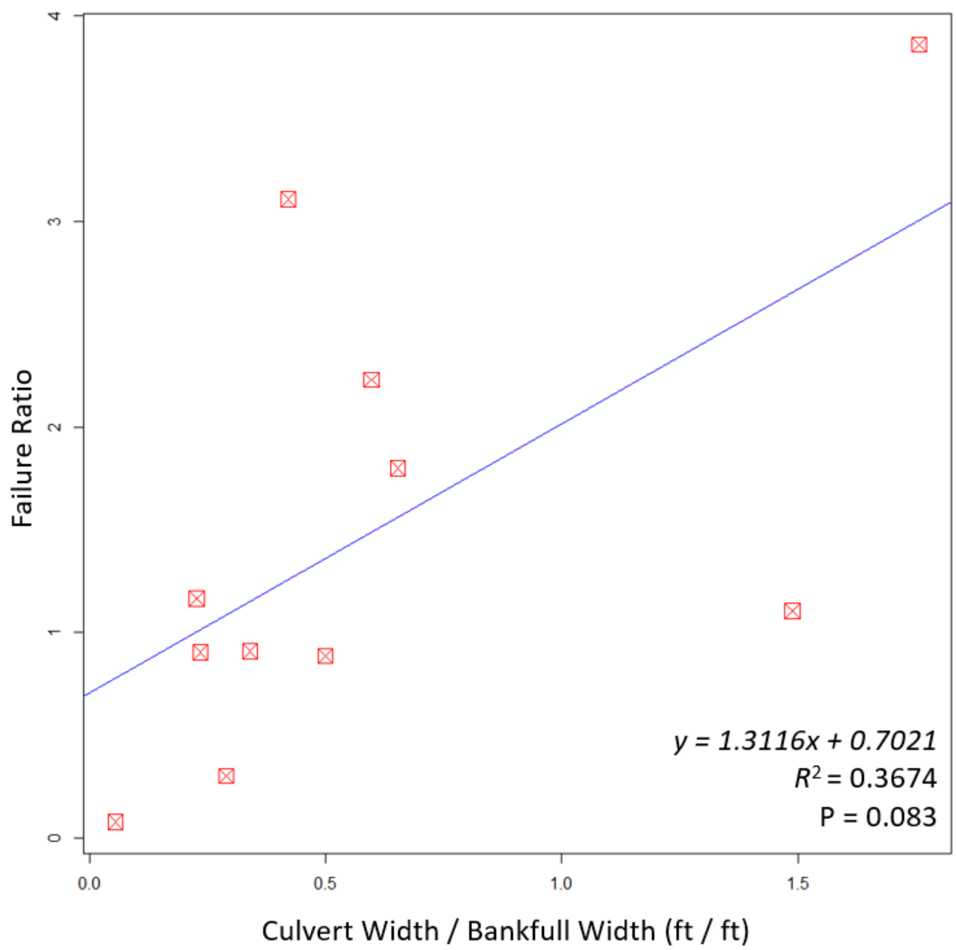

Figure 3.4: Linear regression between failure ratio and metric g (culvert width / bankfull width (ft / ft)), for the sample of 11 surveyed sites.

Multiple regression revealed the following variables have the highest ability to explain the variability of modeled culvert failures: culvert volume (ft^3) (R^2 =0.67) among culvert measurements (Appendix F); bankfull width (ft) among upstream bankfull measurements (R^2 = 0.03) (Appendix G). Upstream main channel length (mi) correlated highest with the culvert failure ratios (R^2 = 0.11), and watershed area (mi^2) (R^2 = 0.05) upstream the culvert was also used in the multiple regression analysis (Appendix E). Our linear analysis created a model with a multiple R^2 value of 0.90, and a combined p-value of 0.004 (Table 3.6).

Table 3.6: Independent variables, individual and combined R^2 and p-values for a multiple linear regression model used to predict culvert failure ratio.

Independent variable	R^2	p-value
Culvert volume (ft^3)	0.67	0.001
Bankfull width (ft)	0.03	0.56
Main channel length (ft)	0.11	0.83
Watershed Area (mi^2)	0.05	0.09
Combined	0.90	0.004

The resulting equation from this regression was:

$$y = 0.504 + 0.0009C_V - 0.005B_W + 0.0233M_L - 0.054W_A \text{..........Equation 5}$$

Where y is the failure ratio, C_V is the culvert volume (ft^3), B_W is bankfull width (ft), M_L is main channel length (mi), and W_A is the watershed area (mi^2).

Failure ratios representing failure condition at unsurveyed culverts in the North Branch were predicted from this equation (Table 3.7). Six of the nine unsurveyed sites have an estimated failure condition less than one, and therefore are predicted to fail at a flood return interval less than 50 years (Figure 3.5).

Table 3.7: Model inputs and estimated failure ratio at unsurveyed culverts in the North Branch.

Site	Culvert volume (ft^3)	Bankfull width (ft)	Main channel length (mi)	Watershed area (mi^2)	Modeled Failure Ratio
GOLD02	1531	36.0	4.3	5.49	1.5
GOLD03	1578	18.4	0.3	0.48	1.8
HOLM02	1500	15.0	2.0	4.68	1.6
HOLM03	284	62.0	1.4	2.81	0.3
MITITRIB01	41	3.5	0.3	0.71	0.5
MITITRIB02	38	5.6	0.9	0.64	0.5
NBPR10	330	16.4	2.4	7.16	0.4
SILK01	13	12.0	0.7	0.14	0.5
UNGOLD01	115	11.5	0.0	0.84	0.5

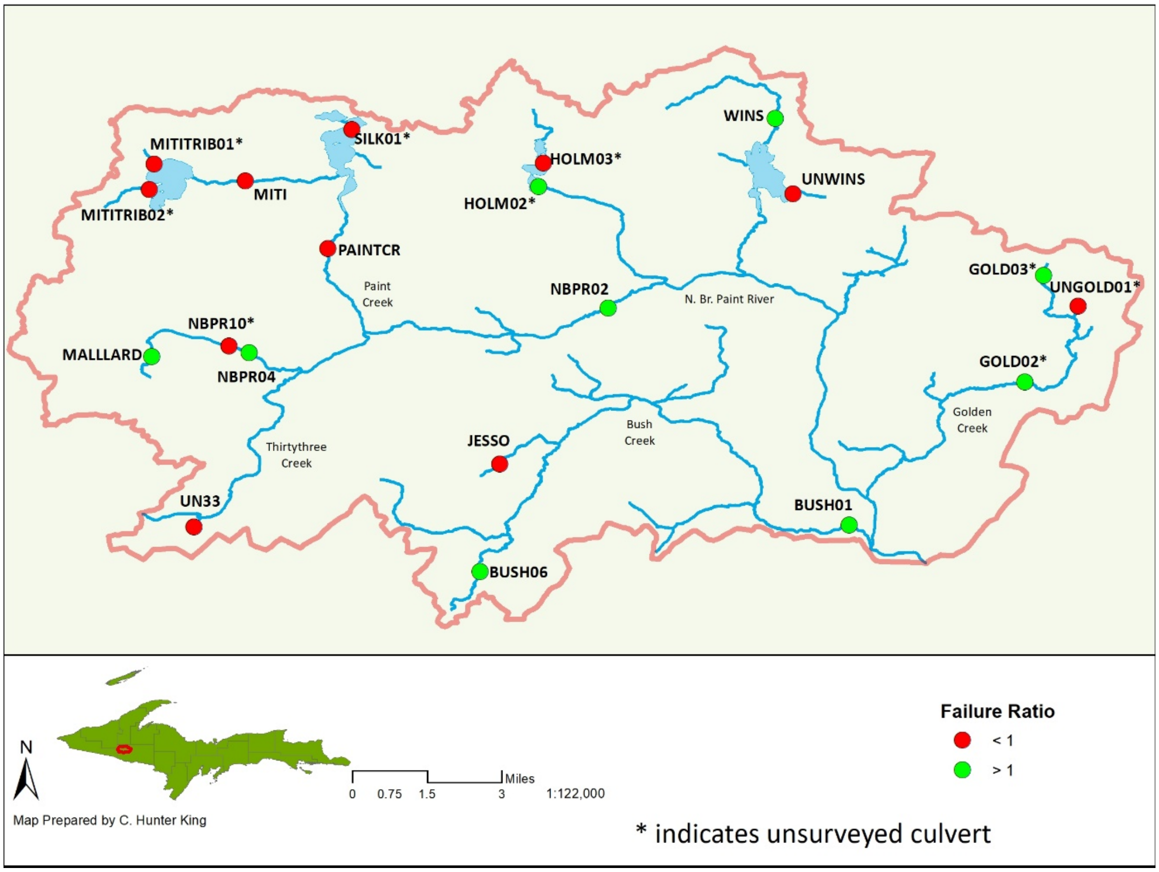

Figure 3.5: Culvert location and predicted failure ratio.

Four of the nine culverts with a passability score of 0 have potential to fail at a discharge less than Q50 (Table 3.8). The three perched culverts in the North Branch, are predicted to fail at a discharge less than Q50 (Table 3.8).

Table 3.8: Site, passability score, and predicted failure ratio at each culvert in the North Branch. Asterisks (*) indicate perched culverts.

Site	Passability Score	Predicted Failure Ratio
BUSH01	0	3.1
BUSH06	0	3.9
GOLD02	0	1.5
GOLD03	0	1.8
HOLM02	0	1.6
HOLM03	0	0.3
JESSO*	0	0.3
UN33*	0	0.9
UNWINS*	0	0.9
MALLLARD	0.5	1.2
MITI	0.9	0.9
MITITRIB01	0.9	0.5
MITITRIB02	0.9	0.5
NBPR02	0.9	1.8
NBPR04	0.9	2.2
NBPR10	0.9	0.4
PAINTCR	0.9	0.1
SILK01	0.9	0.5
UNGOLD01	0.9	0.5
WINS	1	1.1

3.4 Economic Implications of a Culvert Replacement in the North Branch

Cost of replacement (C_R) estimates for surveyed sites in the North Branch are averaged $104,090 in 2017 dollars and ranged from $13,341 to $171,450. Service costs ($C_S$) estimated for planned and failed replacements averaged $20,818 and $31,227, respectively, across sites (Table 3.9).

Table 3.9: Total cost of replacement (C_R), service cost of planned replacement (C_{SP}), and service cost of failed replacement (C_{SF}) for each site.

Site	Total Cost of Replacement (C_R)	Service cost of Planned Replacement (20% of C_R) (C_{SP})	Service cost of Failed Replacement (30% of C_R) (C_{SF})
BUSH01	$171,450	$34,290	$51,435
BUSH06	$32,526	$6,505	$9,758
JESSO	$107,924	$21,585	$32,377
MALLARD	$171,450	$34,290	$51,435
MITI	$49,635	$9,927	$14,890
NBPR02	$171,450	$34,290	$51,435
NBPR04	$114,300	$22,860	$34,290
PAINTCR	$171,450	$34,290	$51,435
UN33	$27,167	$5,433	$8,150
UNWINS	$114,300	$22,860	$34,290
WINS	$13,341	$2,668	$4,002

User delay costs (C_D) were $599 for a planned culvert replacement lasting two days and $2,996 for a failed culvert replacement, lasting 10 days (Table 3.10).

Table 3.10: Inputs and associated costs to estimate C_{DP} and C_{DF} from Equation 1 and Equation 2.

Input		Planned Delay Cost (C_{DP})	Failure Delay Cost (C_{DF})
T	Daily Traffic	10	10
H	Delay Time (hours)	1	1
D	Days of Replacement	2	10
C_P	Personnel ($ hr^{-1})	$24	$24
V_P	% Passenger Traffic	97	97
V_O	Occupancy	1.2	1.2
C_F	Freight ($ hr^{-1})	$70	$70
V_F	% Truck Traffic	3	3
C_D	Cost Estimate	$599	$2,996

Cost of sediment replacement (C_G) ranged from $377 to $5,945 at surveyed sites in the North Branch (Table 3.11). Cost of sediment removal (C_E) from the downstream channel averaged $6,017 and ranged from $4,485 to $9,285 across sites (Table 3.11).

Table 3.11: Sediment loss, fill replacement cost (C_G), and sediment removal cost (C_E) at surveyed sites.

Site	Sediment Loss (yd^3)	Fill Replacement Cost (C_G)	Sediment Removal Cost (C_E)
BUSH01	75	$2,175	$6,035
BUSH06	57	$1,653	$5,585
JESSO	49	$1,421	$5,385
MALLARD	111	$3,219	$6,935
MITI	123	$3,567	$7,235
NBPR02	205	$5,945	$9,285
NBPR04	104	$3,016	$6,760
PAINTCR	40	$1,160	$5,160
UN33	15	$435	$4,535
UNWINS	25	$725	$4,785
WINS	13	$377	$4,485

Total cost of a planned culvert replacement (T_P) averaged $124,963 and ranged from $16,009 at WINS to $206,339 at BUSH01. Total costs of a replacement after failure (T_F) were 11% to 39% more than T_P, and averaged 19% more throughout analyzed sites (Table 3.12). The increase in cost varied with the complexity of the size and number of structures (pipes) at each crossing, and the relative amounts of sediment mobilized at failure.

Table 3.12: Estimated total planned cost of replacement, total failure cost of replacement, and the percent increase in cost because of culvert failure for each site.

Site	Total Planned Cost of Replacement (T_P)	Total Failure Cost of Replacement (T_F)	Percent Increase
BUSH01	$206,339	$234,091	13%
BUSH06	$39,032	$49,522	27%
JESSO	$129,509	$147,108	14%
MALLARD	$205,740	$233,039	13%
MITI	$59,562	$75,327	26%
NBPR02	$205,740	$238,115	16%
NBPR04	$137,160	$158,366	15%
PAINTCR	$205,740	$229,205	11%
UN33	$32,600	$40,287	24%
UNWINS	$137,160	$154,100	12%
WINS	$16,009	$22,205	39%
Average	$124,963	$143,760	19%

Estimated costs of planned replacement for the nine unsurveyed culvert sites in the North Branch averaged $127,005 and ranged from $14,970 to $205,380. Assuming a 19% increase in cost to replace each culvert after failure, emergency replacement ranged from $17,811 to $245,115 at the unsurveyed culverts in the North Branch (Table 3.13).

Table 3.13: Estimates for total planned and failure costs of replacement at unsurveyed culverts in the North Branch.

Site	Total Planned Cost of Replacement	Total Failure Cost of Replacement
UNGOLD	$137,519	$163,648
GOLD02	$205,979	$245,115
GOLD03	$137,519	$163,648
HOLM02	$137,519	$163,648
HOLM03	$205,979	$245,115
MITITRIB01	$14,968	$17,811
MITITRIB02	$28,527	$33,947
SILK02	$137,519	$163,648
NBPR10	$137,519	$163,648
Average	$127,005	$151,136

4 Discussion

4.1 Predictors of Culvert Failure

As storms with increased intensity are occurring more often throughout the Great Lakes Basin (Changnon and Kunkel, 1995), the probability of culvert failure because of insufficient capacity is also increasing, and therefore prioritizing stream crossings based on potential risk of failure should be considered. Wissink et al. (2005) argue that if a published review of culvert failures were to take place, the mechanisms of failure may be just as numerous as the number of failures. The interaction between culvert attributes, road composition, soil, upstream watershed conditions, and climate make failure identifiers difficult to quantify, especially across large areas and varying climate. Through multiple regression, this study identified that the individual attributes of culvert volume, upstream bankfull width, upstream main channel length, and upstream watershed area were good predictors of failure conditions at culverts. Though the equation in this study (Equation 5) may be over-fit and will need more data to develop a reliable model. Using culvert and upstream measurements that fall within the range of those in the North Branch multiple regression, failure ratios can be predicted at culverts in other watersheds in the northern Great Lakes Basin. Metric a (Table 3.4) can be used to estimate failure risk at a culvert. When applied across a sample of culverts, Metric a will indicate the relative probability that a culvert will fail under a commonly used design discharge (Q50). Through comparing culvert width to upstream bankfull width (metric g, Table 3.4), or constriction ratio, potential failure conditions can also be predicted at a culvert. For example, PAINTCR had a constriction ratio of 0.056 and a predicted failure return interval of 1 year, while at the other end of the range in the North Branch, BUSH06 had a constriction ratio of 1.76 and a predicted failure return interval of >500 years (Table 3.4). Applying this simple analysis across a broad population of culverts will aid in prioritization for risk of failure, as the culverts with smaller constriction ratios are at higher risk of failing at closer occurring return interval. After a major flooding event in New England states in 2012, 100% of culverts located in or near towns with constriction ratios <0.5 failed (Gillespie et al., 2014). Although our study watershed was not located in or near a town, there is relationship between constriction ratio, risk of failure, and fish passage throughout watersheds with differing landuse.

These metrics could be used in the screening process for culvert replacement prioritization. By using USDA Forest Service recommendations, such as culverts that simulate the natural stream channel in terms of bankfull width and natural substrate throughout, risk of failure will be reduced at sites where channel constriction is measured (Gubernick et al., 2008). One example of a prioritization based on our results would be to replace culverts with a constriction ratio less than 0.5 with larger or more effective crossings, such as stream simulating culverts. Although stream simulating culverts are normally more costly than traditional culvert designs at implementation (Gillespie et. al., 2014), stream simulation culverts mimic the characteristics of the natural stream and allow unobstructed organism passage. A wide range of flood flows and associated wood and sediment loads are also able to pass through the stream simulation structures (Gubernick et al., 2008; Diebel et al., 2009; Cenderelli et al., 2011).

4.2 Fish Passability

The removal or remediation of a potential barrier to aquatic organism passage may increase stream connectivity. Observations from this study infer that passability and risk of failure can be associated in the North Branch. Nine culverts had passability ratings of 0, and of the nine, four were predicted to fail within the 50-year flood return interval. The other 11 culverts with passability rank of 0.5, 0.9, and 1 had a predicted failure flood return that ranged from the 1 year to >500 year. The three surveyed culverts that had perched outlets (passability

0) also predicted Qtop return periods of less than 35-years, therefore a perched culvert should be ranked highest for replacement in terms of both fish passability and risk of failure.

The majority of culverts that are passable (score 0.5, 0.9, 1) were scored 0.9, indicating that the culverts are barriers to fish only at high flows. Due to predictions of intense precipitation events occurring more often in the Great Lakes, these culverts will be less passable more often throughout the year (Kunkel, 2003; Groisman et al., 2005; Brandt et al., 2010; d'Orgeville et al., 2014). Fish passability scores are typically acquired from the field during a single visit, and often during periods of lower flow when streams are accessible .These one-time ratings may not be an accurate predictor of fish passability throughout the year or during periods of high flow. Spring run-off is necessary for many important fish in the Great Lakes to reach suitable spawning habitat, including; steelhead, walleye, sturgeon, and white sucker (Kling et. al, 2003). These seasonal high flows associated with snowmelt may decrease passability at a culvert with score 0.9 to 0.5 or even 0. Partial plugging due to ice in the culvert, or beaver activity may also impact passability scores. If fish passability is the overarching rationale for replacing a culvert, focal fish taxon population densities should be referred to in different stream reaches with impassable barriers (McKay et al., 2016). If more of the focal taxon occurs in a particular reach, or if there is documented decline in fish populations, we suggest that a more detailed survey and analysis of stream impairments be conducted. It is possible that connectivity could be addressed by prioritizing low passability or high failure risk culverts with improved designs. However, other negative pressure may also be affecting local fish populations, and this can only be accurately assessed using more detailed field surveys and analysis. .

4.3 **Effects of Climate on Culvert Failure**

The regression equations that best predicted flood discharge estimates at the North Branch were established in 1984 (Holtschlag and Crosky, 1984). Even using these relatively dated equations, we found that the 100-yr 24-hr rainfall intensity based on the average from 1944-2012 (NOAA, 2013) was a better predictor of observed discharge in the three reference streams than the intensity derived from the period 1909-1957 (USDC, 1961). This suggests that the climate has shifted sufficiently between these periods to affect the flood frequency response of the streams in the region. USGS regression equations are the most accepted statistical method to estimate flood frequency for ungaged streams (Dawdy et al., 2012) and updating the regression equations may lead to even more accurate flood predictions.

In an analysis by Groisman et al. (2005), Michigan, Wisconsin, Minnesota, Illinois, and Ohio experienced a 20% increase in the frequency of intense precipitation (upper 0.3% daily precipitation) from 1893-2002. Kunkel (2003) concludes that 5 year 24 hour storm events have increased 4% per decade since 1900. About 85% of these storm events occurred between the months of May and September with roughly 90% of the trend attributed to increasing temperatures in the region. By 2050 the median 50-year return precipitation amount in the Great Lakes Basin is projected to increase by 14%-29%, increasing potential discharge (d'Orgeville et al., 2014). Total precipitation is projected to increase in the Great Lakes basin during winter months, and Brandt et al. (2010) caution that current precipitation measurements should not be used in hydrologic predictions in the Great Lakes. Acquisition of the annual peak flow distribution from USGS stream gaged data in the culvert prioritization area of interest will make future climate predictions more precise. Because snowmelt is a major hydrologic input in the upper Great Lakes (Wu and Johnston, 2006), models that emphasize winter precipitation predictions should be used to acquire future potential peak discharges.

One possible extension of this study would be to use predicted regional precipitation increases to recalculate the distribution of discharges using the USGS equations and convey the ratio of discharge at culvert failure to a future Q50. Kling et al. (2003) found that two Great Lakes regionalized general circulation models (PCM and HadCM3) predicted 100-yr 24-hr precipitation events to increase, if not double, by 2100. An estimated discharge of 1,741 $ft^3\ s^{-1}$ is predicted where the North Branch joins the South Branch Paint River for the Q50 event using the current (NOAA, 2013) 100-yr 24-hr precipitation value of 5.8 in hr^{-1}. Assuming the precipitation will double over the next century and all the other coefficients in the USGS regression equations for Michigan remain constant, the calculated future discharge would be 5,139 $f^3\ s^{-1}$, nearly three times the current estimate. (Holtschlag and Crosky, 1984, Kling et. al., 2003).

4.4 Age of Infrastructure and Culvert Failure

The age of surveyed culvert is one key trait that can lead to culvert failure and was not accounted for in this study. The useful design life for corrugated metal pipe ranges from 35 to 50 years, and concrete ranges from 50-100+ years (Perrin and Jhaveri, 2004). Najafi et al. (2008) conclude that the majority of stream crossings and drainage infrastructure in the USA is nearing, if not already passed, the end of their design life. Culvert failure rates are also high near the beginning of their life due to improper installation or manufacturing problems (Najafi, 2005). If the culvert is installed at erroneous elevation or slope compared with the natural stream conditions, or if the structure does not have adequate bedding material, one major discharge may cause failure within a few years of installation. Thus, the relationship between probability of structural failure and time creates a “bathtub” curve with high probability of culvert failure at installation, low probability of failure during the remainder of the design life, and increased probability of failure after the design life has been surpassed (Najafi, 2005). By adding a rank associated with years-post-installation, probability of failure due to culvert age can be included in the prioritization process. For example, age-of-culvert scores could be low for the first 0-5 years, then increase and be constant for age 6-40 culverts, then decrease back to the original implementation score for culverts that exceed 40 years of age. This age-of- structure score could then be added to the passability score and failure ratio estimated for the culvert. Summing of these scores would provide a simple prioritization ranking where a lower value would indicate a culvert that should be replaced sooner than one with a higher score, though there is less rationale to replace a new culvert, unless there is observable malfunction due to improper installment. For example, a culvert age 0-5 could have an age-of structure of 0.5, age 6-40 could have a score of 1, and a 40+ year-old culvert could have a score of 0.1. Such that, a 31 year old culvert with a failure ratio of 0.8, and a fish passability score of 0.9 would have a prioritization ranking of 2.7. As that same culvert ages another decade, assuming no changes to failure ratio and passability scores, the prioritization rank would decrease to 1.8. This type of application, across a large number of culverts will provide a ranking system that addresses risk of failure, passability, and age of the culvert.

4.5 Economic Impact of Single and Multiple Failures

Costs of individual culvert failure vary due to size of structure(s) and the amount of sediment and fill mobilized from the road prism at failure. Larger storms may road fill wider than downstream bankfull width to mobilize into the downstream channel and floodplain. To accommodate more potential sediment loss, a width estimate greater than downstream bankfull could be used (Equation 4). A suite of assumptions could be used to identify costs attributed to loss of riverine ecosystem service at a culvert failure location (Levine, 2013). This study used the cost to remove sediment from the stream channel as a mechanism to estimate this added cost at failure. Loss of recreation, water quality for municipal use, and navigation values are not accounted for, and could be important for particular river systems.

To apply an economic application to river connectivity for fish, a cost benefit analysis could be created where the benefit is stream connectivity and the cost is the net present value investment of the culvert of interest. To acquire the stream connectivity, one could simply multiply the amount of miles upstream of the culvert with the passability score subtracted from one. The net present value could be estimated by subtracting the present value of an emergency culvert replacement from the planned cost of culvert replacement. The output of this cost benefit analysis would be in dollars per mile, and could be used in situations where fish passability is strongly weighted.

Cumulative impacts associated with multiple failures within the watershed from the same storm were not taken into account in the economic analysis of this study. An event producing Q50 would potentially cause 11 of the 20 surveyed culverts to fail, and replacing these would cost $1.4 million after the emergency using the per-culvert replacement costs. Realistically, a large storm producing multiple failures would increase the cost estimates from this study, which were developed based on the replacement of a single culvert. The majority of the added costs would come from; insufficient availability of labor resulting in added delays and service costs. The delay cost does not account for higher value delay estimates such as emergency vehicle access or response time, or prolonged detours lasting longer than an hour. To create a more accurate estimate of the cost associated with user delay, detour and daily durations can be manipulated in Equation 3 (Section 2.7). Estimates for these added costs are dependent on a suite of assumptions such as, permanent human residency in the watershed, age of residents, and local commerce (Perrin and Jhaveri, 2004). Because of the reliance of the delay cost on the population density, estimates of the total cost of a culvert failure would likely increase in areas with greater development. The North Branch is located in Iron County, MI, U.S.A, which has a population density of 9 people per square mile (US Census Bureau A, 2016), which is less than other counties in the northern Great Lakes region such as, for example, Antrim County, MI, U.S.A (48 people per square mile) (US Census Bureau B, 2016). Another unrecognized cost in the individual replacement analysis is the cost of financing, which may not be an issue for single replacements and therefore is an appropriate simplification for single culvert failure analysis. However, for large storms such as the Q50 that would potentially take out 11 culverts in the North Branch, the financing availability and cost may be significant and this could further extend the time needed to complete the repairs.

4.6 Recommendations

It is recognized that free flowing freshwater ecosystems are critical and increase the wellbeing of humanity (Brisbane Declaration, 2007). Poff et al. (2015) argue for new water management models that call for collaboration of water resource engineers, conservation ecologists, and stakeholders to engage and collaborate in the decision-making process.

By using either the individual metrics, multiple linear regression or fish passability scoring, a map could be created for a given watershed, similar to Figure 3.5, where a green point indicates a culvert with low risk of failure or high passability, and a red point indicates a culvert with high risk of failure or low passability. By visually representing culverts in space, simple assumptions and decisions can be made pertaining to the amount of stream that would be reconnected with a given replacement. By integrating or associating a prioritization score, such as one described above in Section 4.3, recommendations can be made to remove or replace a culvert based on both fish passability and risk of failure. Culverts with failure ratios close to 1 or a combined passability and failure rating in the middle of the group of analyzed culverts could be assessed using more rigorous methods. In these cases, given available time and funds, surveying with a total station and doing hydraulic modeling with a model such as HEC-RAS might help identify culverts that are on the margin of the priority list. If there are river reaches that are more suitable for fish habitat or populations, or where habitat restoration has been made a priority, more weight could be given in the prioritization to fish passability. Regardless of the method of prioritization, if a culvert is targeted for upgrade, the stream simulation design should be considered for the replacement culvert to create more natural hydrologic and ecologic stream dynamics.

Given the small sample size of potential barriers in the North Branch, more analysis on other small subwatersheds would strengthen the predictive ability of the metrics. Also, this study focused on prioritizing potential barriers in relatively undeveloped forests in the northern Great Lakes Basin, and our results should apply to other watersheds with similar attributes. The North Branch has very low developed land, and negligible amount of land used for agriculture as compared to other parts of the northern Great Lakes Basin. Using our approach on other watersheds with higher rates of impervious or agricultural land use would also increase confidence in the metrics we identified as good predictors of the risk of culvert failure at high flows.

5 Conclusion

We estimated the impacts associated with stream crossing infrastructure in low-order streams in Northern Michigan. Because culverts have the greatest risk of failure, we analyzed the economic and ecologic implications of potential culvert failure. We identified all the structures in the North Branch Paint River watershed and applied fish passability ratings and the Great Lakes Road Crossing Inventory Instructions (GLRCII) for each structure. We also calculated the discharge that would cause the headwater to depth ratio to exceed one and the return interval associated with this discharge for a sample of 11 culverts and associated stream segments that were surveyed. This study identified predictors from the relatively easily obtained measurements from the GLRCII and tested their ability to predict potential failure. Two metrics had high predictive ability. The first metric was culvert width times main channel length divided by watershed area ((ft x ft) / ft^2). This metric implies that failure condition is more likely when a narrower culvert is placed at a location with a relatively wide mean upstream watershed width. The second metric that correlated strongly with failure is culvert width divided by bankfull width, which represents the degree of channel constriction. This metric implies that as the upstream channel is constricted by a culvert inlet, the probability of failure increases. We estimated the cost of culvert replacement following failure would average 19% more than planned culvert replacements. By applying this analysis of the risk of failure in the prioritization process for culvert replacements, potential economic and environmental costs could be avoided, particularly as storms become more intense in the Great Lakes Basin as the climate changes.

6 References

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7 Appendices

Appendix A: Great Lakes Road Crossing Inventory Instructions (GLRCII) field data sheet (GLRSCII, 2011):

Stream Crossing Data Sheet Site ID: ____

General Information

Stream Name: ____ Road Name: ____

Name of Observer(s): ____ Date: ____

GPS Waypoint: ____ GPS Lat/Long: ____

County: ____ Township: ____ Range: ____ Sec: ____

Adjacent Landowner Information: ____ Additional Comments: ____

Crossing Information

Crossing Type: Culvert(s) no.: ____ Bridge Ford Dam Other: ____

Structure Shape: Round Square/Rectangle Open Bottom Square/Rectangle Pipe Arch Open Bottom Arch Ellipse

Inlet Type: Projecting Mitered Headwall Apron Wingwall 10-30° or 30-70° Trash Rack Other

Outlet Type: At Stream Grade Cascade over Riprap Freefall into Pool Freefall onto Riprap Outlet Apron Other

Structure Material: Metal Concrete Plastic Wood

Substrate in Structure: None Sand Gravel Rock Mixture

General Condition: New Good Fair Poor

Plugged: ____ % Inlet Outlet In Pipe

Crushed: ____ % Inlet Outlet In Pipe

Rusted Through? Yes No Structure Interior: Smooth Corrugated

Multiple Culverts/Spans

Number the culverts/spans left to right, facing downstream. Include #s in site sketch on back page

Culvert/ Span #	Width (ft)	Length (ft)	Height (ft)	Material

Structure Length (ft):[1] ____ Structure Width (ft):[1] ____ Structure Height (ft):[1] ____

Structure Water Depth (ft):[1] inlet ____ outlet ____ Perch Height (ft):[1] ____ or NA

Embedded Depth of Structure (ft):[1] inlet ____ outlet ____

Structure Water Velocity (ft/sec):[1] inlet ____ outlet ____

Structure Water Velocity Measured: At Surface or ____ ft Below Surface Measured With: Meter or Float Test

Stream Information

Stream Flow: None < ½ Bankfull < Bankfull = Bankfull > Bankfull

Scour Pool (if present) Length: ____ Width: ____ Depth: ____ Upstream Pond (if present) Length: ____ Width: ____

Riffle Information (measured in a riffle outside of zone of influence of crossing)

Water Depth (ft): ____ Bankfull Width (ft): ____ Wetted Width (ft): ____ Water Velocity (ft/sec): ____

Dominant Substrate: Cobble Gravel Sand Organics Clay Bedrock Silt Measured With: Meter or Float Test

Road Information

Type: Federal State County Town Tribal Private Other:

Road Surface: Paved Gravel Sand Native Surface Condition: Good Fair Poor

Road Width at Culvert (ft): ____ Location of Low Point: At Stream Other Runoff Path: Roadway Ditch

Embankment: Upstream Fill Depth (ft): ____ Slope: Vertical 1:1.5 1:2 >1:2

Downstream Fill Depth (ft): ____ Slope: Vertical 1:1.5 1:2 >1:2

Left Approach: Length (ft): ____ Slope: 0% 1-5% 6-10% >10% Ditch Vegetation: None Partial Heavy

Right Approach: Length (ft): ____ Slope: 0% 1-5% 6-10% >10% Ditch Vegetation: None Partial Heavy

[1] - Fill out for primary culvert (culvert #1). If multiple culverts are used, number each and use embedded table.

Form Date: February 28, 2011

Appendix A continued: Great Lakes Road Crossing Inventory Instructions (GLRCII) field data sheet (GLRSCII 2011):

Erosion Information

Use a new row for each distinct gully/erosion location. Note prominent streambank erosion within 50 feet of crossing.

Location of Erosion Ditch, approach, or streambank Left or right facing downstream	Erosion Dimensions (ft)			Eroded Material Reaching Stream?		Material Eroded Sand, Silt, Clay, Gravel, Loam, Sandy Loam or Gravelly Loam.
	Length	Width	Depth			
				Yes	No	
				Yes	No	
				Yes	No	
				Yes	No	
				Yes	No	

If there is erosion occurring, can corrective actions, such as road drainage measures, be installed to address the problem? Y N

Extent of Erosion: Minor Moderate Severe Stabilized

Erosion Notes:

Photos – enter photo number in blank corresponding to location

❑ Site ID ____ ❑ Upstream Conditions ____ ❑ Downstream Conditions ____

❑ Inlet ____ ❑ Outlet ____ ❑ Road Approach – Left ____ ❑ Road Approach – Right ____

Summary Information

Would you consider this a priority site? Fish Passage Erosion Why?

Would you recommend a future visit to this site? Yes No Why?

Were any non-native invasive species observed at the site? Yes No If yes, what species were observed?

Site Sketch

Draw an overhead sketch of crossing. Be sure to mark North on the map and to indicate the direction of flow. Include major features documented on form, such as erosion sites, multiple culverts, scour pool, impounded water, etc.

Form Date: February 28, 2011

Appendix B:

Table B.1 Cross-watershed comparisons of return interval discharge values (ft^3/s) from Log-Pearson Type 3 (LP3) analysis of observed data; USGS Wisconsin Zone 4 regression equation; USGS Michigan Zone 1 regression (I) using 1961 24-hr precipitation value; USGS Michigan Zone 1 regression (II) using 2013 24-hr precipitation value; and MDEQ method for the Middle Branch Ontonagon River, Black River, and Iron River (USGS, 1982).

Return Interval	Log Pearson Type 3	USGS Wisconsin Regression	MDEQ	USGS Michigan Regression I	USGS Michigan Regression II
Mid. Br. Ontonagon River (164 mi^2)					
2	806	733	192	806	902
5	1,162	927	373	1,108	1,334
10	1,406	1,083	549	1,299	1,605
25	1,726	1,287	864	1,553	1,993
50	1,967	1,444	1,167	1,749	2,309
100	2,215	1,822	1,547	1,954	2,655
Iron River (92 mi^2)					
2	459	394	155	380	408
5	634	525	293	537	602
10	744	622	424	640	730
25	878	748	653	778	909
50	973	843	869	885	1,052
Black River (184 mi^2))					
2	3,784	2,008	537	2,297	2,747
5	5,998	2,488	972	3,280	4,397
10	7,541	2,907	1,382	3,900	5,449
25	9,547	3,459	2,095	4,754	7,054
50	11,066	3,891	2,758	5,439	8,436
100	12,595	4,991	3,587	6,161	10,005

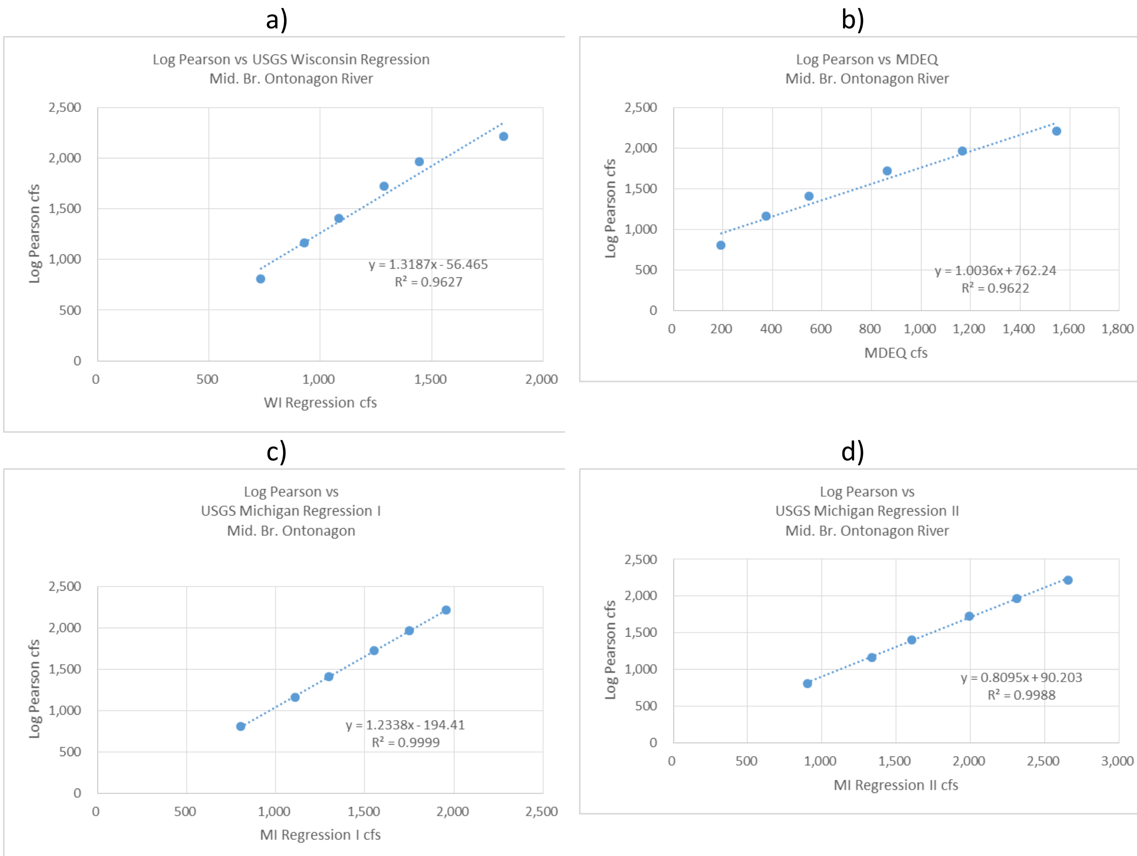

Figure B.1: Linear regression comparing the four peak discharge model outputs with LP3 estimates at the USGS gage on the Middle Branch Ontonagon River (USGS C, 2016).

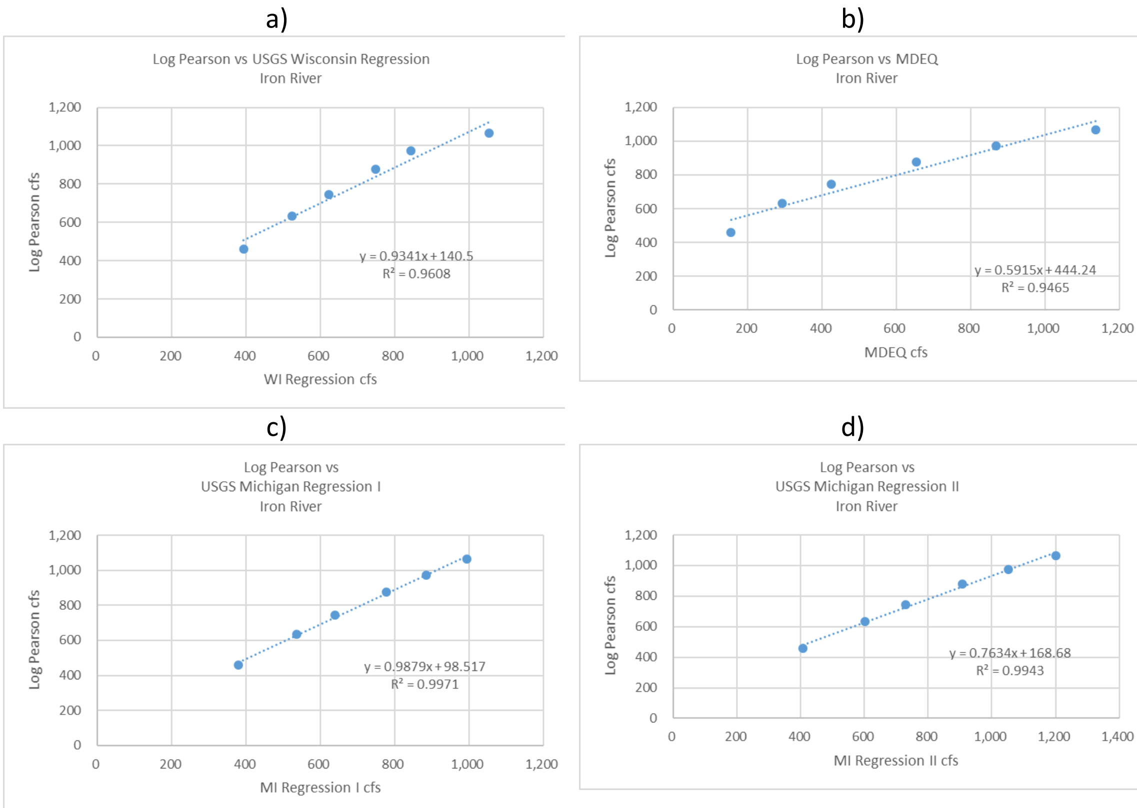

Figure B.2: Linear regression comparing the four peak discharge model outputs with LP3 estimates at the USGS gage on the Iron River (USGS B, 2016).

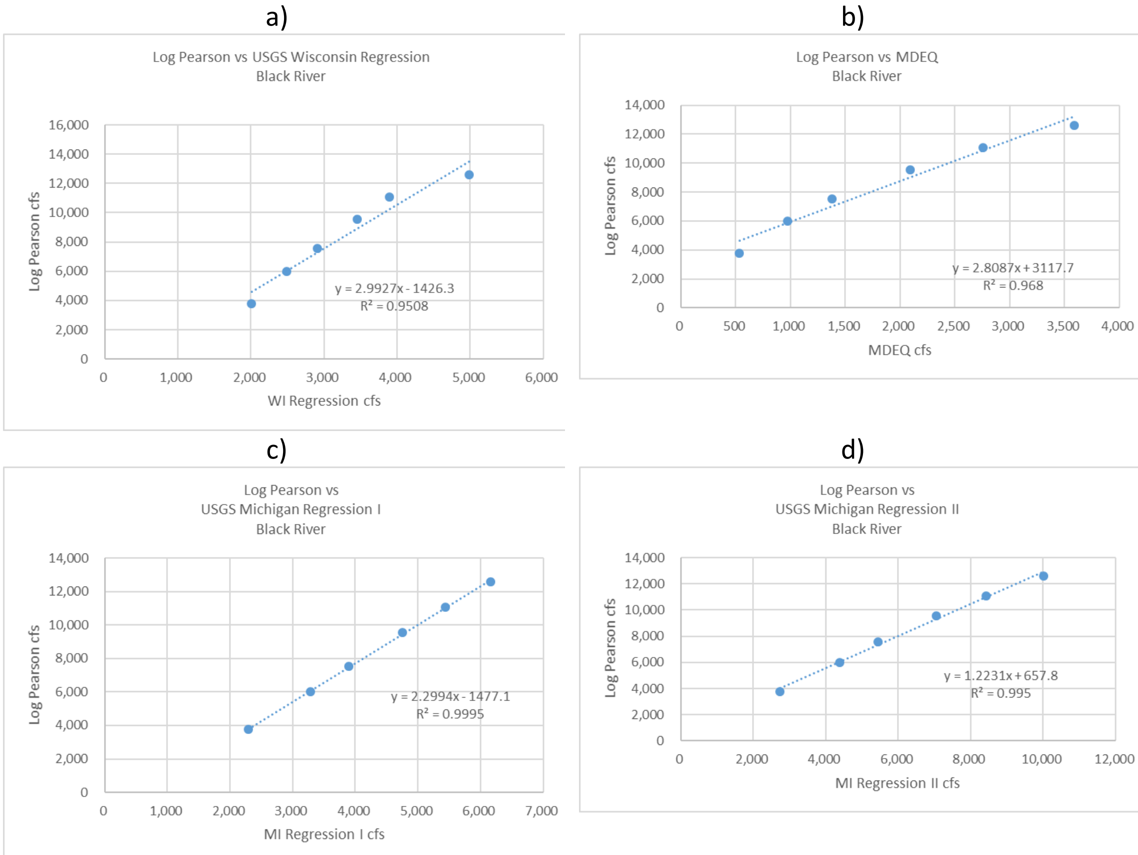

Figure B.2: Linear regression comparing the four peak discharge model outputs with LP3 estimates at the USGS gage on the Black River (USGS A, 2016).

Appendix C: USGS Michigan Zone 1 regression equations for Q5, Q10, Q25, Q50, and Q100:

$$Q5 = 0.9890*10^{0.6869}\,CA^{0.8931}\,S^{0.2164}\,(CS+1)^{-0.1741}\,SR^{-0.1148}\,I^{1.0458}\,(OW+1)^{-0.1524}\,(M+1)^{0.1669}\,(FT+1)^{0.1017}\,(MT+1)^{0.0884}\,(C+1)^{0.0905}\,(BR+1)^{0.0963}\,(CT+1)^{0.0400}$$

$$Q10 = 0.9840*10^{0.6688}\,CA^{0.8902}\,S^{0.2256}\,(CS+1)^{-0.1749}\,SR^{-0.1280}\,I^{1.1936}\,(OW+1)^{-0.1548}\,(M+1)^{0.1660}\,(FT+1)^{0.1100}\,(MT+1)^{0.1004}\,(C+1)^{0.0999}\,(BR+1)^{0.0901}\,(CT+1)^{0.0443}$$

$$Q25 = 0.9790*10^{0.6099}\,CA^{0.8878}\,S^{0.2372}\,(CS+1)^{-0.1744}\,SR^{-0.1351}\,I^{1.4077}\,(OW+1)^{-0.1564}\,(M+1)^{0.1666}\,(FT+1)^{0.1194}\,(MT+1)^{0.1117}\,(C+1)^{0.1091}\,(BR+1)^{0.0831}\,(CT+1)^{0.0489}$$

$$Q50 = 0.9761*10^{0.5569}\,CA^{0.8860}\,S^{0.2464}\,(CS+1)^{-0.1738}\,SR^{-0.1414}\,I^{1.5657}\,(OW+1)^{-0.1569}\,(M+1)^{0.1681}\,(FT+1)^{0.1254}\,(MT+1)^{0.1184}\,(C+1)^{0.1142}\,(BR+1)^{0.0784}\,(CT+1)^{0.0521}$$

$$Q100 = 0.9741*10^{0.4936}\,CA^{0.8853}\,S^{0.2558}\,(CS+1)^{-0.1727}\,SR^{-0.1487}\,I^{1.7299}\,(OW+1)^{-0.1574}\,(M+1)^{0.1703}\,(FT+1)^{0.1308}\,(MT+1)^{0.1242}\,(C+1)^{0.1181}\,(BR+1)^{0.0740}\,(CT+1)^{0.0539}$$

Where inputs are:

CA = contributing drainage area (mi^2)
S = main channel slope (ft/mi)
CS = river channel length adjacent to swamp, wetlands and open water bodies (ft)
SR = slenderness ratio (hydraulic $length^2$/CA)
I = 100yr-24 hr precipitation intensity per the 2013 NOAA Atlas (5.81 in)
OW = postglacial alluvium (sand/gravel) in watershed, soil types 3, 7, 8 (%)
M = postglacial muck and peat in watershed, soil type 2 (%)
FT = postglacial fine-textured till in watershed soil type 10 (%)
MT = postglacial medium-textured till in watershed soil type 10, 11(%)
C = lacustrine clay and silt in watershed, soil type 5 (%)
BR = bedrock in watershed, soil type 15 (%)
CT = postglacial coarse-textured till in watershed, soil type 13 (%)

Appendix D: Coarse inventory data: site, latitude, longitude, potential barrier type, barrier material, barrier dimensions, and fish passability score.

Site ID	Latitude	Longitude	Type	Material	Length (ft)	Width (ft)	Height (ft)	Passability Score
BUSH03	46.2602	-88.7679	Bridge	Metal	12.0	40.3	3.9	0
BUSH04	46.2664	-88.7740	Bridge	Metal/Conc.	16.4	43.5	8.5	0.5
BUSH05	46.2590	-88.8279	Bridge	Wood	15.0	24.5	5.3	0.5
BUSH07	46.2435	-88.8392	Bridge	Metal/Wood	7.0	55.5	6.0	0.9
BUSH08	46.2631	-88.7716	Bridge	Wood	2.8	15.5	3.0	0.9
MITI02	46.3439	-88.9297	Bridge	Metal/Conc./Wood	12.0	50.0	4.4	1
NBPR01	46.3156	-88.7714	Bridge	Metal/Concrete	16.7	49.5	7.2	1
NBPR03	46.2988	-88.8762	Bridge	Metal/Concrete	17.9	59.0	4.9	1
NBPR05	46.2994	-88.8527	Bridge	Metal/Wood	5.3	75.0	5.7	1
NBPR06	46.2620	-88.7446	Bridge	Wood	5.0	100.5	5.6	1
NBPR07	46.2879	-88.8959	Bridge	Wood	4.8	43.5	2.0	1
NBPR09	46.2981	-88.7464	Bridge	Metal/Conc./Wood	10.0	130.0	6.4	1
PNTCR01	46.3059	-88.8824	Bridge	Wood	6.0	31.5	2.1	1
PNTCR03	46.2991	-88.8801	Bridge	Metal/Wood	8.0	24.5	4.3	1
POST01	46.2421	-88.8654	Bridge	Metal/Conc.	39.5	24.0	5.7	1
THREE01	46.2818	-88.9071	Bridge	Metal/Concrete	40.3	20.0	7.0	1
THREE02	46.2464	-88.9303	Bridge	Metal/Concrete	32.0	12.0	4.7	1
WINS01	46.3333	-88.7655	Bridge	Concrete	20.4	24.3	3.6	1
NBPR08	46.2917	-88.8899	Bridge	Metal/Wood	6.0	50.0	5.5	1
BUSH06	46.2296	-88.8464	Culvert	Metal	54.4	13.8	5.9	0
GOLD02	46.2847	-88.6883	Culvert	Metal	39.3	8.0	6.2	0
GOLD03	46.3156	-88.6828	Culvert	Metal	60.0	6.2	5.4	0
HOLM02	46.3414	-88.8295	Culvert	Metal	44.5	7.4	5.8	0
HOLM03	46.3483	-88.8279	Culvert	Metal	19.0	5.0	3.8	0
JESSO	46.2608	-88.8407	Culvert	Metal	36.0	2.9	2.1	0
MALLARD	46.2921	-88.9417	Culvert	Metal	48.8	7.5	4.2	0.5
MITI	46.3430	-88.9146	Culvert	Metal	46.0	8.0	5.6	0.9
MITITRIB01	46.3479	-88.9411	Culvert	Concrete	33.0	2.5	2.5	0.9
MITITRIB02	46.3405	-88.9425	Culvert	Metal	30.0	2.5	2.5	0.9
NBPR04	46.2931	-88.9135	Culvert	Metal	45.0	10.8	7.1	0.9
NBPR10	46.2951	-88.9193	Culvert	Metal	20.0	6.0	3.5	0.9
PAINTCR	46.3235	-88.8906	Culvert	Metal	23.6	5.0	5.0	0.9
SILK01	46.3580	-88.8836	Culvert	Metal	19.5	1.3	1.3	0.9
UNGOLD01	46.2891	-88.6612	Culvert	Metal	35.5	2.3	1.8	0.9
UN33	46.2426	-88.9294	Culvert	Metal	36.0	3.0	3.0	0
UNWINS	46.3393	-88.7555	Culvert	Metal	34.5	3.0	3.0	0
BUSH01	46.2431	-88.7393	Double_Cul	Metal	45.3*	21.5**	7.0*	0
NBPR02	46.3061	-88.8092	Double_Cul	Metal	24.9*	3.5**	7.1*	0.9
WINS	46.3612	-88.7606	Triple_Cul	Metal/Plastic	32.3*	6.7**	3.9*	1
DAM10	46.3022	-88.8186	Dam	Debris	21.0	20.0	4.5	0
EPNTDAM01	46.3509	-88.8824	Dam	Earthen Berm	25.8	5.4	2.0	0
HOLMDAM01	46.3238	-88.8063	Dam	Earthen Berm	49.0	60.0	5.7	0
MALDAM01	46.2951	-88.9193	Dam	Open Crest	0.5	7.0	4.3	0
NBPRDAM01	46.2992	-88.8798	Dam	Open Crest	7.5	29.0	1.8	0
NBPRDAM02	46.2998	-88.8640	Dam	Open Crest	10.5	8.0	1.0	0
PAINTDAM01	46.3338	-88.8854	Dam	Earthen Berm	174.0	16.0	2.6	0
WINSDAM01	46.3337	-88.7653	Dam	Earthen Berm	32.0	20.8	3.5	0
HOLM01	46.3375	-88.8139	Ford	NA	8.0	47.6	NA	1
UNKNBPR01	46.2983	-88.8228	Ford	NA	8.5	7.9	NA	1

*averaged length and height at double/triple culverts, ** combined width at double/triple culverts

Appendix E: Surveyed culvert sites and the respective failure ratio, watershed attributes, and coefficients derived by comparing failure ratio with attributes.

Site	failure ratio	watershed slope	area weighted permeability	main channel length	total channel length	hydraulic length	watershed area	storage area	main channel slope
		%	in/hr	ft	ft	ft^2	ft^2	ft^2	%
BUSH01	3.1	2.8	6.3	67901	135643	73341	672705792	154167552	0.24
BUSH06	3.9	2.6	6.4	6088	6088	8044	44719741	6651786	0.70
JESSO	0.3	3.1	2.8	1997	1997	8553	24086938	4583209	0.97
MALLARD	1.2	2.8	6.1	3392	3906	9513	78065096	32991299	0.39
MITI	0.9	3.8	5.5	12938	16971	19862	169821274	54223488	0.50
NBPR02	1.8	3.2	8.2	62864	146786	67746	1284112558	372915418	0.12
NBPR04	2.2	4.1	6.6	14492	14492	20391	204412792	75388769	0.08
PAINTCR	0.1	3.6	6.6	30994	47150	37927	392527872	129913344	0.20
UN33	0.9	2.4	13.0	362	362	7920	14809006	2135485	0.35
UNWINS	0.9	1.5	9.5	2273	2273	6500	14443799	5623073	0.39
WINS	1.1	1.8	8.7	14642	16483	18526	71273917	34583155	0.25
R		-0.007	-0.048	0.331	0.325	0.287	0.220	0.149	-0.075
R^2		0.00005	0.002	0.110	0.106	0.082	0.048	0.022	0.006
P		0.135	0.079	0.010	0.236	0.029	0.440	0.008	0.158

Appendix F: Surveyed culvert sites and the respective failure ratio, culvert dimensions, and R^2 values derived by comparing failure ratio with dimensions.

Site	failure ratio	culvert slope	culvert width	culvert height	culvert length	culvert inlet area	culvert volume
		%	ft	ft	ft	ft^2	ft^3
BUSH01	3.109	0.6	21.5	7.0	45.3	95.0	4300.1
BUSH06	3.860	0.8	13.8	5.9	54.4	56.5	3076.3
JESSO	0.299	2.1	2.9	2.1	36.0	4.8	172.2
MALLARD	1.163	2.7	7.5	4.2	48.8	27.7	1350.9
MITI	0.907	0.4	8.0	5.6	46.0	35.2	1618.7
NBPR02	1.799	3.0	23.5	7.1	24.9	158.4	3944.2
NBPR04	2.230	1.2	10.8	7.1	45.0	60.0	2697.8
PAINTCR	0.076	1.7	5.0	5.0	23.6	19.6	463.7
UN33	0.885	0.4	3.0	3.0	36.0	7.1	254.5
UNWINS	0.902	0.2	3.0	3.0	34.5	7.1	243.9
WINS	1.104	2.3	6.7	3.9	32.3	19.4	624.0
R		-0.201	0.706	0.657	0.624	0.558	0.817
R^2		0.040	0.498	0.432	0.389	0.311	0.667
P		0.876	0.905	0.557	0.971	0.518	0.448

Appendix G: Surveyed culvert site and the respective failure ratio, upstream bankfull conditions, and R^2 values derived by comparing failure ratio with conditions.

Site	failure ratio	bankfull width ft	average bankfull depth ft	bankfull area ft^2
BUSH01	3.109	51.0	1.7	88.3
BUSH06	3.860	7.8	1.0	12.8
JESSO	0.299	10.0	0.6	4.7
MALLARD	1.163	33.0	0.8	12.7
MITI	0.907	23.5	1.7	44.0
NBPR02	1.799	36.0	2.8	108.8
NBPR04	2.230	18.0	0.4	7.6
PAINTCR	0.076	89.2	1.6	135.5
UN33	0.885	6.0	0.4	4.2
UNWINS	0.902	12.8	1.5	41.6
WINS	1.104	4.5	0.4	7.1
R		-0.163	0.095	-0.076
R^2		0.0266	0.009	0.0058
P		0.994	0.616	0.780

Appendix H: Metric, metric description, units, R values, and R^2 values of all metrics used in correlations.

Metric	Metric description	Units in equation	R	R^2
a	(culvert weight x main channel length)/watershed area	ft^2 / ft^2	0.835	0.697
b	(culvert width x hydraulic length)/watershed area	ft^2 / ft^2	0.800	0.640
c	culvert height/culvert width	ft / ft	-0.708	0.501
d	culvert width/culvert height	ft / ft	0.683	0.467
e	(culvert length x total channel length)/watershed area	ft^2 / ft^2	0.683	0.466
f	culvert width/hydraulic length	ft / ft	0.670	0.449
g	culvert width/bankfull width	ft / ft	0.606	0.367
h	(culvert length x total channel length)/watershed area	ft^2 / ft^2	0.605	0.366
i	inlet area/storage area	ft^2 / ft^2	0.597	0.356
j	culvert length/culvert width	ft / ft	-0.568	0.323
k	(culvert width x culvert length)/bankfull area	ft^2 / ft^2	0.545	0.297
l	inlet area/watershed area	ft^2 / ft^2	0.542	0.294
m	inlet area/bankfull area	ft^2 / ft^2	0.523	0.274
n	bankfull width/cuvlert width	ft / ft	-0.520	0.271
o	hydraulic length/culvert width	ft / ft	-0.513	0.263
p	(culvert length x main channel length)/watershed area	ft^2 / ft^2	0.503	0.253
q	bankfull area/inlet area	ft^2 / ft^2	-0.483	0.234
r	(culvert width x culvert length)/watershed area	ft^2 / ft^2	0.468	0.219
s	bankfull area/(culvert width x culvert length)	ft^2 / ft^2	-0.450	0.202
t	storage area/inlet area	ft^2 / ft^2	-0.413	0.171
u	bankfulll width/culvert height	ft / ft	-0.388	0.151
v	main channel slenderness ratio	mi^2 / mi^2	0.386	0.149
w	culvert width/culvert length	ft / ft	0.383	0.147
x	watershed area/inlet area	ft^2 / ft^2	-0.376	0.141
y	culvert height/hydraulic length	ft / ft	0.375	0.141
z	culvert height/bankfull width	ft / ft	0.353	0.125

Appendix H continued: Metric, metric description, units, R values, and R^2 values of all metrics used in correlations.

Metric	Metric description	Units in equation	R	R^2
aa	(total channel length x watershed slope)/(culvert length x culvert slope)	(ft^2 x %) / (ft^2 x %)	0.351	0.123
ab	(culvert inlet area x culvert slope)/(watershed area x watershed slope)	(ft^2 x %) / (ft^2 x %)	0.347	0.120
ac	hydraulic length/watershed area	mi / mi^2	-0.344	0.118
ad	(culvert length x culvert slope)/(total channel length x watershed slope)	(ft x %) / (ft x %)	-0.324	0.105
ae	culvert length/culvert height	ft / ft	-0.313	0.098
af	(main channel length x main channel slope)/(culvert length x culvert slope)	(ft x %) / (ft x %)	0.304	0.092
ag	bankfull width/cuvlert length	ft / ft	-0.290	0.084
ah	total channel length/watershed area	mi / mi^2	0.280	0.078
ai	watershed area/(culvert width x culvert length)	ft^2 / ft^2	-0.270	0.073
aj	hydraulic length/total channel length	mi / mi	-0.244	0.060
ak	(watershed area x watershed slope)/(culvert inlet area x culvert slope)	(ft^2 x %) / (ft^2 x %)	-0.231	0.054
al	main channel length/culvert height	ft / ft	0.231	0.053
am	(culvert length x culvert slope)/(main channel length x main channel slope)	(ft x %) / (ft x %)	-0.227	0.052
an	culvert length/main channel length	ft / ft	-0.220	0.048
ao	(hydraulic length x watershed slope)/(culvert length x culvert slope)	(ft x %) / (ft x %)	0.216	0.047
ap	cuvlert length/bankfull width	ft / ft	0.200	0.040
aq	100 yr 24 hr precipitation intensity/area weighted permeability*	(in/hr) / (in/hr)	-0.195	0.038
ar	main channel length/culvert width	ft / ft	-0.192	0.037
as	culvert height/main channel length	ft / ft	-0.185	0.034
at	(culvert length x hydraulic length)/watershed area	ft^2 / ft^2	-0.185	0.034
au	culvert slope/watershed slope	% / %	-0.183	0.034
av	main channel length/watershed area	mi / mi^2	0.165	0.027
aw	main channel length/culvert length	ft / ft	0.149	0.022
ax	culvert length/hydraulic length	ft / ft	0.136	0.019
ay	culvert height/culvert length	ft / ft	0.132	0.018
az	main channel length/total channel length	mi / mi	-0.115	0.013

* uses the NOAA, 2013 precipitation intensity (5.81 $inhr^{-1}$)

Appendix H continued: Metric, metric description, units, R values, and R^2 values of all metrics used in correlations.

Metric	Metric description	Units in equation	R	R^2
ba	hydraulic lengthslenderness ratio	mi^2 / mi^2	0.113	0.013
bb	culvert width/main channel length	ft / ft	-0.088	0.008
bc	main channel slope/culvert slope	% / %	-0.088	0.008
bd	hydraulic length/culvert length	ft / ft	0.087	0.008
be	(culvert length x culvert slope)/(hydraulic length x watershed slope)	(ft x %) / (ft x %)	-0.074	0.005
bf	hydraulic length/culvert height	ft / ft	0.070	0.005
bg	area weighted permeability/100 yr 24 hr precipitation intensity*	(in/hr) / (in/hr)	-0.048	0.002
bh	watershed slope/culvert slope	% / %	-0.048	0.002
bi	culvert slope/main channel slope	% / %	0.046	0.002

* uses the NOAA, 2013 precipitation intensity (5.81 $inhr^{-1}$)